Schemes for Building an Efficient All-Optical Virtual Private Network

By

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Most importantly, I would thank my parents and my wife for their continuous encouragement and support during my studies. This thesis is dedicated to my wife, whom I have first met shortly after I began my MPhil studies at The Chinese University of Hong Kong.

ABSTRACT

In this thesis, we target on two key elements for building an efficient all-optical VPN. First we propose a heuristic method for maximizing the utilization of a survivable multi-ring WDM network without wavelength conversion, and next is the design of an all-optical VPN processing engine.

For maximizing the utilization of a survivable multi-ring WDM network without wavelength conversion, we assume that the network is supporting packet and circuit based services simultaneously. The packet based service is used to support a public IP network while the circuit based service is ideal for providing optical VPN. We propose a heuristic method to re-partition the wavelengths on the active and protection rings to improve the network's wavelength utilization. The main contribution of this scheme is to jointly consider the effect of packet and circuit based services on WDM rings to enhance wavelength utilization.

For the design of an all-optical VPN processing engine, we will make a conceptual design based on known properties of optical elements. We assume such elements to function under ideal conditions and do not consider any cost issues. The contribution of this design is to overcome a bottleneck in today's optical VPN solution, which consist of different classes of optical networking switches with an electronic VPN processing engine. The objective of the all-optical VPN processing engine is to realize the potential bandwidth of an all-optical network when providing VPN service. While our design may not be feasible for actual implementation with today's technology, it will serve as a roadmap for further development when the necessary advancements in optical components emerge.

Combining the two schemes in this thesis, we will be coming closer toward the realization of a wavelength efficient all-optical VPN.

摘要

本論文對建做一個高效能全光虛擬私有網絡（All-Optical VPN）提出兩種構想。我們首先提出一種不帶波長轉換（wavelength conversion）的啓發式程序去優化一個帶保護性波分覆用多環網（survivable multi-ring WDM network）的通道利用率，然後再爲全光虛擬私有網絡而設計一個全光合式處理引擎（All-Optical VPN Processing Engine）。

在優化一個帶保護性波分覆用多環網的通道利用率時，我們需要假設網絡上同時地支持基於封包式和電路式的連接。封包式的連接一般會用於公用 IP 網，而電路式的連接則是用於提供全光虛擬私有網服務的理想方式。由我們提出的啓發式程序是在波分覆用多環網的平臺上把工作和保護通道作綜合式的考慮重新分配，目的是要達至優化通道利用率。

在構思爲全光虛擬私有網絡而設的全光合式處理引擎時，我們基於已知光元件的特性而提出一個概念式的設計。我們假設該等元件將會在理想的環境下工作及不考慮成本因素。其設計主要是針對現時光虛擬私有網在光電轉換後處理而構成的較能瓶頸。我們的目標是要令光虛擬私有網能達到全光網絡的潛在頻寬。雖然我們的設計不一定能在現時的技術下有效地實現，但光元件技術還是在不斷進步中，我們只期望爲以後的發展立下路標。

本論文的貢獻是希望在結合我們提出的兩種構想後可實現一個優化的高效能全光虛擬私有網絡。

TABLE OF CONTENTS

List of Figures

Chapter 1

1. Introduction

1.1. Optical Networks

Since the mid 1960's, it has been shown that optical fibres have enormous bandwidth potential for communication applications and it will transport voice/data/video faster and further than any electrical media. In today's networks, more data are being passed over fibres than copper. Optical networking have evolved from being a simple transmission media at Layer 1 in traditional ATM and SONET/SDH networks to becoming a multiple access domain with WDM (wavelength division multiplexing) networks.

The cost of optical networking components is in continuous decline to allow technologies that were once only applied in backbone networks to be available in metropolitan and access networks. Recent researches in networking technologies and protocols all indicate that the future of networking will converge at the optical layer.

1.1.1. IP over Optical Networks

The explosive growth of the Internet has led the Internet Protocol (IP) to become a preferred common platform for linking all types of networks and devices. In the early stages of optical networking development, the rationale behind implementing a multilayered network was because low speed data access and voice traffic could not efficiently occupy an optical channel on their own; hence multiple aggregation layers were employed for more efficient use of bandwidth [1].

Today, access and backbone networks have grown to have similar granularities, and high capacity service interfaces like Gigabit Ethernet (GE) and 10GE are gaining popularity at the access layer [2] (Figure 1-1 and Figure 1-2). Legacy multilayered networks offer less value to groom traffic toward the backbone and it is often more economical to launch these services directly into the optical network. Hence today's multilayered networks become costly to scale, maintain and operate because each layer must be individually controlled, managed and engineered. Traditional protocol stacks (IP/AAL5/ATM/SONET/WDM or IP/PPP/HDLC/SONET/WDM) are over engineered for next generation optical networks and offer low bandwidth efficiency [3].

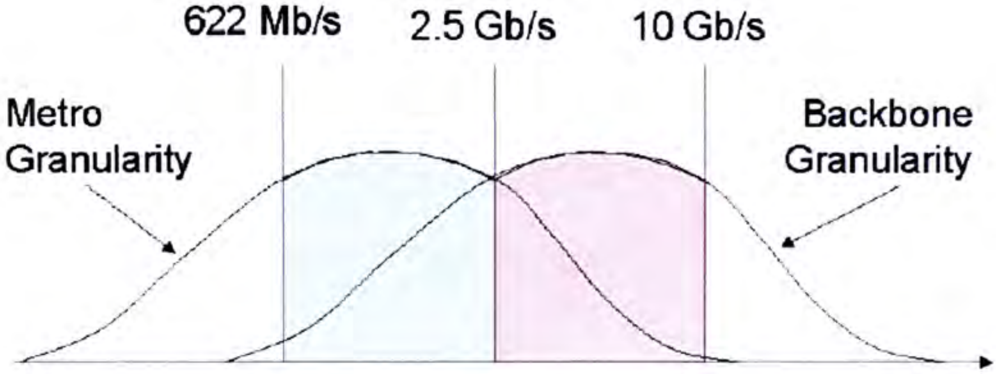

Figure 1-1 Access network traffic has 4x smaller granularity than backbone network in 1996 [2]

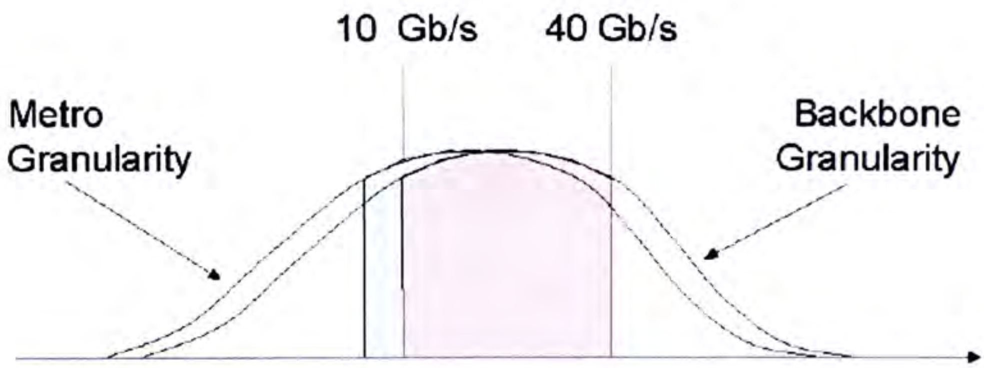

Figure 1-2 Access network traffic grows to have similar granularity as backbone network by 2006 [2]

In attempt to lower the cost of operating a multilayered network, the industry already had several endeavours to bring IP into the optical layer. From the Packet over SONET and IP over ATM, to the more recent attentions on IP over WDM, all of them are designed to transfer some of IP's intelligence and flexibility from the packet world into the optical layer by separating the functionality of service creation and optical transport under a unified control plane (Figure 1-3). The result is improved network efficiency by deploying smart optical networking devices.

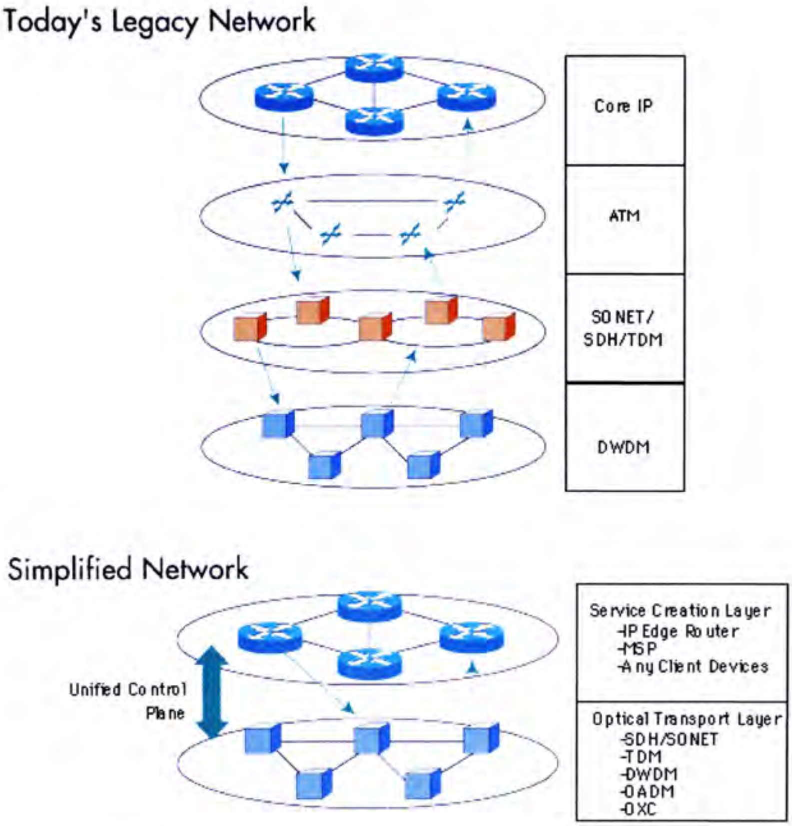

Figure 1-3 Bringing IP closer to the optical layer [4]

Many recent developments on networking protocols have expanded their application beyond IP into the optical domain. The most obvious examples are Optical-BGP (OBGP) and Generalized MPLS (GMPLS).

OBGP is an extension to BGP for lightpath provisioning and aims to allow an optical network node to trigger the routing and switching of a lightpath [5]. When applied to the Internet, OBGP could lead to on-demand massive direct peering by optical connections. As the cost for ISP to purchase Internet transit bandwidth is still high, the ability to have on demand direct peering could lead to potential cost savings.

Since the Internet Engineering Task Force (IETF) formally announced Multiprotocol Label Switching (MPLS) in 1997, it has enhanced the performance and efficiency of traditional IP routing by separating the data and the control planes, thus effectively merging the benefit of ATM into IP. However, MPLS is still a strictly data networking protocol and have no direct application in optical networks.

Following the interest of MPLS in the packet world, talks on MPλS have begun to emerge in 1999. MPλS is meant to be an extension of MPLS for optical networks by defining MPLS's "label" as wavelengths (λ), and MPLS's Label Switching Router (LSR) as optical cross-connects (OXC). However, MPλS did not take off because wavelength conversion devices required for optical-label switching are not yet feasible enough to be implemented in commercial networks.

MPλS later evolved into GMPLS, which is a multi-platform control plane technology to support devices that perform switching in time, space, and wavelength domains [6]. In contrast to MPλS, GMPLS allows the control plane to be physically diverse from the associated data plane. For example, a packet switching label switching path (LSP) may be nested in the subordinate time-division multiplexing LSP, which in turn is nested in another lambda-switched LSP.

1.1.2. Challenges in Optical Networks

Due to survivability issues, optical networks are traditionally designed in rings. By nature of the dedicated access medium, the working and protection path in SONET/SDH forms a 1+1 redundant relationship. While reliable, survivable SONET/SDH rings are limited in terms of the efficiency of their bandwidth utilization and flexibility, 50% of the usable bandwidth is effectively idle, waiting to become active in case of protection switching upon a link failure. The main challenge of finding a method to provide greater flexibility and more efficient use of resources is to overcome the limitation of QoS.

At the turn of this century, the volume of data packet traffic has exceeded voice TDM traffic on public networks. As the cost of transporting the data packets goes down and Voice over IP (VoIP) technology becoming mature, voice traffic slowly become just another form of data. It becomes reasonable to assume that traffic transported over today's WDM links mostly originated from IP routers. Therefore, it is desirable to optimize the overall cost and manageability of an optical IP network and it spark off researches in novel optical networking components to meet this goal.

One basic requirement for an intelligent optical network is its ability to reconfigure. Wavelengths and lightpaths are often used as means of traffic engineering. However, the process of lightpath reconfiguration would result in network service interruption. Sometimes the benefits of reconfiguration can outweigh its cost when traffic changes are quasi-static [7]. Research in dynamically reconfigurable optical network with minimal service impact is of great interest.

1.2. Virtual Private Networks (VPN)

The demand for IP Virtual Private Network (VPN) has been riding on the explosive growth of the Internet and the popularity of IP networks in enterprises. VPNs are logically partitioned private networks constructed over a public infrastructure which offers traffic separation and data privacy. Users of a VPN should enjoy the same security, reliability, and manageability as in their own private networks. VPN may be implemented in a number of ways over different network infrastructures with different technologies.

1.2.1. CE Based VPN

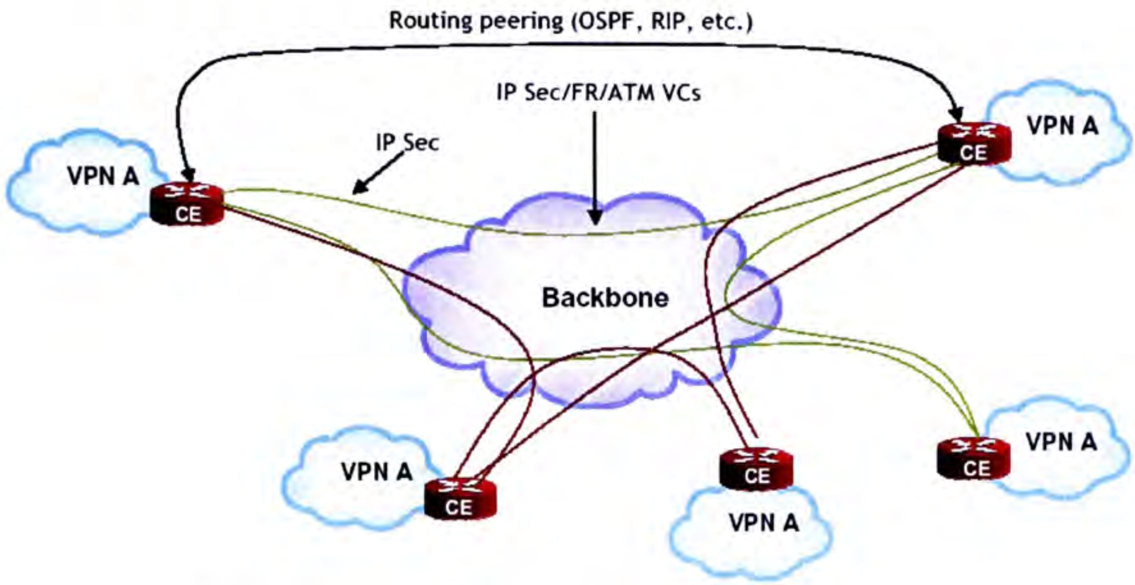

Figure 1-4 CE based VPN reference model [8]

Virtual tunnels are initiated and terminated on the Customer Edge (CE) devices using network tunnelling protocols such as IPsec and L2TP as illustrated in Figure 1-4. Sometimes this is also known as the overlay model because the VPNs are superimposed on a service provider's backbone network by CE devices.

The advantage of a CE based VPN is that it does not require any direct support from the service provider network besides simple IP connectivity. Its disadvantage is that each CE device must have knowledge about the VPN's topology, which means the customer themselves are responsible for the management of their own VPN. Also, any-to-any site connectivity requires all CE in the VPN to be fully meshed which would quickly become a scalability bottleneck.

1.2.2. Network Based VPN

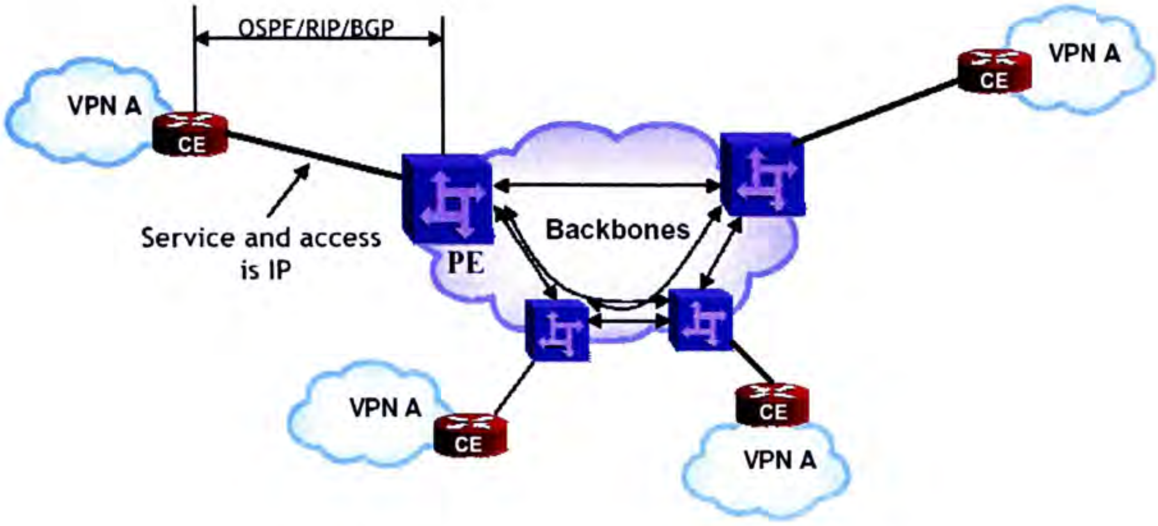

Figure 1-5 Network based VPN reference model [8]

As the demand for VPN raises, service providers realize that they can enhance their network to provide VPN as a value added service to their customers. In this approach, CE devices would only need to peer with the Provider Edge (PE) devices with a single connection, the PE will discover each customer's VPN topology and route to other VPN sites as illustrated in Figure 1-5.

The advantage of network based VPN is that it puts the VPN intelligence on the service provider's network instead of on the CE devices. This lowers the technical hurdles for end users to deploy VPN service and allows service providers to offer a cost effective VPN solution to their customers.

The disadvantage of network based VPN is that the customer will lose some control of their network, while the service providers may need to upgrade their network to deal with complicated networking issues associated with supporting network based VPN, such as overlapping IP addresses among different VPN customers.

There are typically two approaches to implement network based VPN. Virtual Router technology partitions each PE with multiple routing tables, which stores each customer's VPN information for forwarding between customer sites. The more popular MPLS VPN is based on RFC2547bis and uses labels to switch VPN traffic between customer sites.

MPLS was first introduced to improve the forwarding speed of IP routers by using a fixed length tag to replace the variable length IP packet header. It has quickly found spread wide application in traffic engineering, VPN, and Quality of Service (QoS) and gradually becomes an important standard for large-scale IP networks. MPLS bears inherent advantages to VPN implementation because its Label Switched Paths (LSP) can act as tunnels in a public network. MPLS VPN provides connectivity between geographically distributed branches of a private network through the use of LSP.

After a MPLS LSP is created, it may bear any layer 2 and layer 3 data packets. Layer 2 packets may be ATM, Frame Relay, Ethernet VLAN or PPP, while layer 3 packets may be IPv4, IPv6 or IPX, etc.

MPLS VPN can be further classified into VPN realized by BGP extension, or VPN realized by LDP extension. Furthermore, MPLS VPN can also be classified into layer 2 VPN and layer 3 VPN according to whether the PE devices participate in VPN routing.

1.2.2.1. MPLS Layer 2 VPN

In light of a mature implementation of MPLS layer 3 VPN (see section 1.2.2.2), the development of MPLS layer 2 VPN is still very active because customers have not yet learn to trust service providers to manage their network routings. Conversely, some service providers prefer a clear demarcation interface to customers and provide only transparent connectivity services.

The latest development in MPLS layer 2 VPN implementations, commonly know as Virtual Private LAN Service (VPLS), have converged into two competing IETF drafts which differs in their control layer protocol.

draft-kompella-ppvpn-l2vpn (VPLS-BGP)

VPLS-BGP uses Multi-protocol Border Gateway Protocol (MP-BGP) as signalling and auto-discovery mechanism. The supporters of this draft believe that using BGP as signalling and auto-discovery protocol can avoid the "n" square full mesh peering problem. Also, the use of BGP as signalling and auto-discovery protocol has been proven in RFC2547 IP VPN.

draft-lasserre-vkompella-ppvpn-vpls (VPLS-LDP)

VPLS-LDP uses Label Distribution Protocol (LDP) as signalling and auto-discovery mechanism. The PE routers would setup full mesh LDP sessions among all nodes with clients on the same VPN.

1.2.2.2. MPLS Layer 3 VPN

The development and deployment of MPLS layer 3 VPN is more mature than its layer 2 variants and have already reached IETF's RFC stage. Extensibility of MPLS layer 3 VPN is broadened by employing route reflectors similar to a BGP network.

Routing information is generally exchanged between PE and CE via ordinary routing protocols. Each PE calculates route according to information from the extensive BGP and generates the route tables related to each VPN.

MPLS layer 3 VPN providers may offer value added service such as Internet access over a single connection to its customer. Multicast applications may also run more efficiently on layer 3 VPN.

1.2.3. Optical VPN

Coupling the advantages of optical technologies at the multi-access layer and IP VPN protocols at the networking layer, Optical VPN (OVPN) quickly became a buzz word in the networking industry as WDM technologies became a de facto standard for upgrading backbone network infrastructures.

OVPN may be considered as private lightpaths belonging to the customers of a service provider network (see Figure 1-6). An OVPN customer may specify the source-destination pairs and the number of lightpaths between them. OVPN providers will support many independent OVPN customers, all requesting different sets of lightpaths.

OVPN providers may also offer protection paths and a service level agreement to its customers. In addition, users of OVPN may themselves be service providers who use the lightpaths to provide sub-wavelength services to their customers.

At a conceptual level, Optical VPNs and IP VPNs share similarities, but they do have some essential differences because they work at different layers of the networking stack. Optical technology belongs to the physical layer, while IP is at the network layer. IP VPNs would carry the actual data packets, with help from encryption and tunnelling protocols for them to remain private, but Optical VPNs simply carve up wavelengths in a ligthpath. When referenced with the traditional definitions of VPN, OVPN may be regarded as one type of layer 2 VPN.

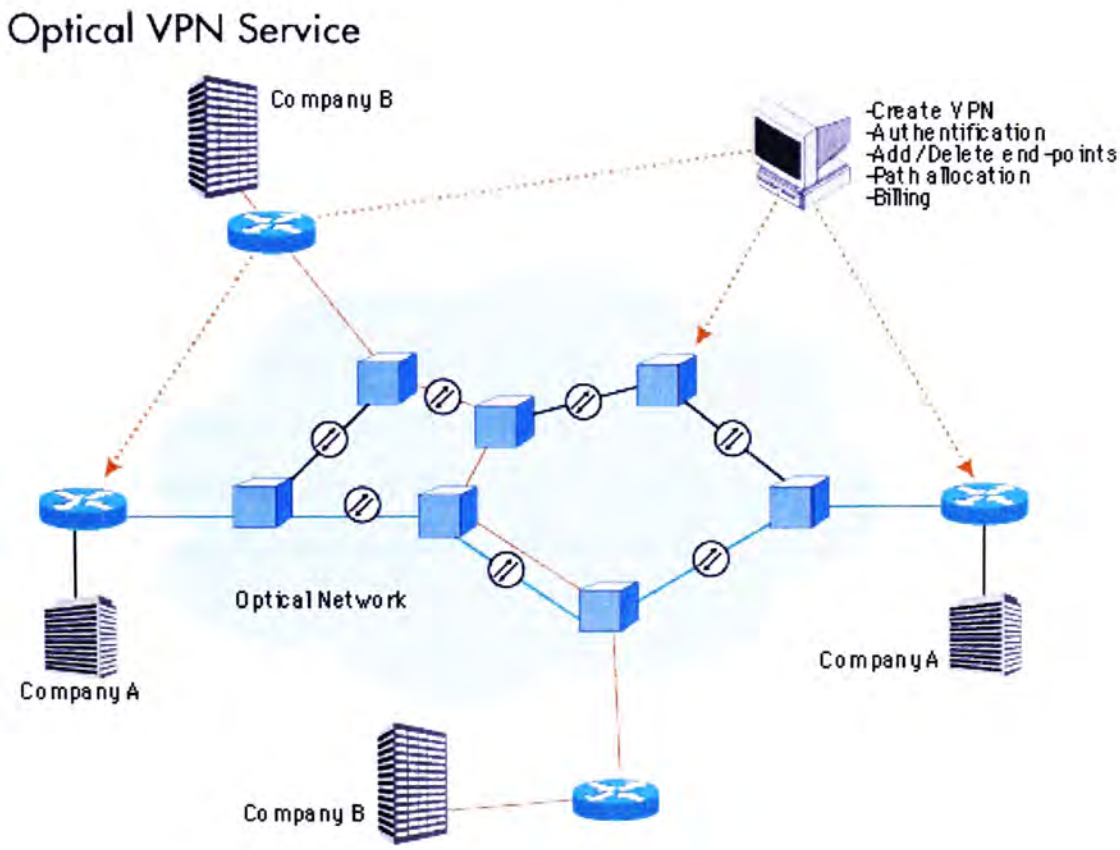

Figure 1-6 Illustration of OVPN on a service provider's optical network [4]

1.2.4. Challenges in VPN Technologies

The emergence of intelligent optical networks and MPLS VPN solutions drive the demand for OVPN services. OVPN providers will face the network engineering and design choices with special considerations given to operation and maintenance issues. There is also demand for innovation in a common platform for control and management under this new intelligent optical infrastructure.

It is particularly important to achieve seamless internetworking as recognized by the efforts of standardization bodies in both the traditional networking and optical domains (e.g., IETF, ITU-T, and OIF). An appropriate intelligent optical network architecture is needed to fulfill these requirements, driven by fundamental advances in optical technologies and the market's expectations for ISPs and carriers to move focus their core business to serve OVPN customers in increasing numbers.

1.3. Objective of this Thesis

In this thesis, we investigate the building blocks of an all-optical virtual private network and propose heuristic methods to improve its efficiency. We will first define the infrastructure for OVPN services which allows dynamic configuration and can support multi-users. We will also identify the interfaces, resources, signalling, and routing protocols that are of interest in an OVPN host network. OVPN service requirements and the main aspects of its invocation, configuration and restoration will be studied.

In particular, we will investigate the combined effect of packet based and optical connection services, and their protection criteria, on the wavelength utilization of a multi-ring WDM network as the platform for OVPN services. We seek to maximize the channel utilization of a survivable multi-ring WDM network without expensive wavelength conversions.

At the optical processing layer, we propose the design of an all-optical VPN processing engine. Our effort will focus on a conceptual design based on known properties of optical elements. We will assume such elements to function under ideal conditions and we do not consider any cost issues. The purpose of this design is to overcome a common bottleneck in today's OVPN implementation, which consist of different classes of optical networking switches with an electronic VPN processing engine. The objective of our all-optical VPN processing engine is to eliminate the OEO traffic path an OVPN in order for it to realize the potential bandwidth of an all-optical network.

Combining the two key components in this thesis, we should be moving closer toward the realization of a wavelength efficient all-optical VPN.

1.4. Outline of this Thesis

Chapter 1: Introduction

This chapter gives a basic overview of optical networks with discussion on enabling optical networks with IP intelligence. It also reviews VPN basics from the traditional VPN to optical VPN.

Chapter 2: Architecture of an All-Optical VPN

This chapter defines the architecture of an all-optical network to support OVPN type of services.

Chapter 3: Maximizing the Utilization of a Survivable Multi-Ring WDM Network

This chapter studies the combined effect of packet based and optical connection services on the wavelength utilization of a survivable optical network.

Chapter 4: Design of an All-Optical VPN Processing Engine

This chapter proposes a novel design of an all-optical processing element with target application on enabling the efficient deployment of OVPN service.

Chapter 5: Conclusion

This chapter summarizes the thesis and call attention to related future works.

Chapter 2

2. Architecture of an All-Optical VPN

2.1. Introduction

Back in the late 1990's, when OC-3 (155Mbps) was considered high-speed and OC-48 (2.5Gbps) was state of the art in the backbone layer. Only "visionaries" in the industry would mention Optical VPN [9] and had confidence that optical access would replace T1 (1.5Mbps) access at the same cost in the near future. Since then, Optical VPN has become a buzz word in the optical networking field.

There are a number of considerations for an optical network architecture supporting Optical VPN (OVPN) service and they are reviewed in this chapter. An overview of OVPN related activities by networking vendors, service providers, and standards bodies are given to examine its current status, followed by studies on OVPN's general requirements, reconfigurability, switching methods, and survivability.

2.2. Networking Vendor Activities

Over the past few years, several networking vendors have rolled out their "OVPN solutions" in an attempt to ignite the market, but so far these attempts have only resulted in smokes because there were more talks by the vendors than actual breakthrough technologies to drive the OVPN applications. OVPN in reality is often minor software enhancements to repackage their "OEO" optical networking gears with "new features." It is worth noting that so far, none of the vendors have delivered real success in commercially deploying true all-optical networking.

Tellium (acquired by Zhone Technologies, http://www.zhone.com) claimed to be the first optical switch company to offer OVPN functionality on their StarNet Optical Services portfolio [10] and gave a demonstration at SUPERCOMM 2002. Since then, Tellium was acquired by Zhone in 2003 and the hype on StarNet has subsided.

Sycamore Networks (http://www.sycamorenet.com) claimed to be among the first to apply IP protocols to optical routing and signalling. It promotes an intelligent optical control plane on its optical switches to envision a flexible, scalable, intelligent optical infrastructure. Sycamore believes it has the best solution to support increasingly dynamic, data-centric communications traffic such as OVPN. It was also the first vendor to announce availability of both GMPLS and UNI 1.0 on an optical switch.

Corvis Equipment (http://www.corvisequipment.com), originally named Nova Telecommunications, Inc., developed and deployed all-optical switches for backbone optical networks since 2000. In 2003, Corvis acquiried Broadwing Communications Services, Inc., an enterprise carrier and IXC, and become the only vertically integrated equipment & service provider in the US.

Alcatel's (http://www.alcatel.com) OVPN solution consists of mainly software products. Using OVPN client software on PC workstations, end users can access the OVPN server, which acts as secured gateway toward the operator's network management system. Customers can manage the set-up, clear down and modification of connections in a flexible way according to the service contract, and monitor the availability and quality of service of their optical VPN in real time.

NEC's (http://www.nec-globalnet.com) OVPN is built upon its IP over WDM solution with a Layered-Mesh Network architecture comprised of networking software and granularity based switching technology, where the functionality of service creation and optical transport are separately managed and controlled through a unified control plane.

Intellambda (http://www.intellambda.com) is currently the latest entrant in the intelligent optical network market. Its product features all-optical wavelength switching with a GMPLS control plane, integrated DWDM transport with advanced optical performance monitoring, and intelligent packet processing with service-oriented data aggregation to create a "service aware" optical network.

2.3. Service Provider Activities

A new class of Optical-switched Service Provider (OSP) has been riding on the wave to promote their service of "fast provisioned flexible point to multipoint managed optical bandwidth service" as OVPN with little successful stories.

One similarity among their optical networking solution is that they all consist of different classes of optical networking switches with an electronic VPN processing engine controlled by software. Therefore, the potential bandwidth of an all-optical network is difficult to achieve.

Storm Telecommunications claims itself to be the first OSP and have announced a strategic partnership with Sycamore Networks in early 2000 to supply it with Intelligent Optical Switches. Storm introduced its revolutionary unmetered "Lightning" optical access service in June 2001 over its European backbone. Pricing is based on flat-rate bandwidth increments, rather than distance or usage. However, this business model has proven to be too early for its times and Storm Telecommunications has gone into bankruptcy in February 2002 having failed to raise additional funding for its bandwidth wholesaling business.

Metromedia Fiber Network (MFN) is a provider of end-to-end optical network and Internet infrastructure solutions. Like Storm Telecommunications, MFN offers unmetered bandwidth at a fixed cost, eliminating the bandwidth barrier and redefining the way broadband capacity is sold. MFN partnered with Nortel Networks in 1999 to launch its WaveChannel Optical Network — the first private, protocol-independent offering to combine voice, data, and video, all on a single network. MFN filed for reorganization under Chapter 11 of the United States Bankruptcy Code in 2002.

Velocita, a fiber-based carrier of carriers entered the market in 1998 as a facilities-based provider of fibre optic infrastructure. In 1999, Velocita won a contract to build AT&T's next generation optical network. In 2001, Velocita partnered with Cisco Systems as its equipment provider to add service offerings such as wavelengths, private line, Internet access and very high-speed virtual private networks. However, Velocita was acquired by AT&T in 2002 after it filed for Chapter 11 bankruptcy protection.

Broadwing Communications (http://www.broadwing.com/) claims to be the first carrier to complete a nationwide, all-optically switched network in the US. Broadwing promote its entire all-optically switched network as controlled from an intelligent, remote management system that enables near real-time provisioning.

2.4. Standard Bodies Activities

Multiple standard bodies in networking and telecommunications are simultaneously driving optical control plane standards, but at the same time, they must collaborate to ensure cohesive development. Their common goal is to improve operational efficiency, network manageability, and service delivery by enabling automated end-to-end provisioning and restoration based on a variety of criteria.

International Telecommunications Union-Telecommunications (ITU-T)

The ITU-T (http://www.itu.int/ITU-T/) has 13 study groups in which representatives of the ITU-T membership develop Recommendations for the various fields of international telecommunications. In particular, Study Group 15 (SG15) focuses on optical & other transport network's control layer for intelligent optical networks.

G.872 Architecture of Optical Transport Networks (OTN) is an elemental recommendations from the T1X1 subcommittee's G.871 Optical Networking Standardization Framework drafted in 1998. OTN provides a reference model which is often referenced by other standards in all-optical networking.

G.8080 Automatic Switched Optical Network (ASON) published in October 2001 by the ITU-T SG-15 provides the foundation for multi-layer interoperability. ASON defines a control and management architecture that effectively creates a dynamic overlay model. Since these models are protocol-independent, GMPLS and other protocols can be mapped to fit within the ITU-T framework as further defined in G.7715 (ASON routing requirements) and G.7715.1 (ASON requirements for link state routing.

Internet Engineering Task Force (IETF)

IETF (http://www.ietf.org), the traditional standardization body of the Internet, is very active in defining a standard optical lightpath provisioning framework by extending MPLS/IP protocols based on generalized interface requirements:

It has resulted in the development of Generalized MPLS (GMPLS) hosted by CCAMP WG (Common Control And Measurement Plane Working Group). It also drafted RSVP-TE and CR-LDP with GMPLS extensions in the signalling domain, OSPF-TE and IS-IS with GMPLS extensions in the routing domain.

The IETF is also responsible for defining the draft of Optical-VPN service within its PPVPN VPN WG (Provider Provisioned VPN Working Group).

Optical Internetworking Forum (OIF)

OIF (http://www.oiforum.com) was founded in April 1998 by a group of networking companies. Its goal is to complement the efforts of other standardization bodies and seek early industry consensus to accelerate technology development and minimize vendor-specific approaches.

OIF focuses on application of IETF protocols in an overlay model. The most important contribution of OIF towards optical-VPN is in defining the IP-centric control and signalling for optical paths and optical user-to-network interface (O-UNI). UNI 1.0 was issued in October 2001 and UNI 2.0 will be based on ITU-T's G.8080 ASON architecture.

2.5. Requirements for All-Optical VPN

The requirements of an all-optical VPN are in many ways similar to a regular VPN and may share the same network based VPN reference model as discussed in Section 1.2. Service requirements of OVPN have been studied by the IETF's PPVPN WG and resulted in an Internet Draft [13].

OVPN can be defined as a collection of ports that connects CE from the same organization to the service provider network, which could support multiple OVPNs.

Therefore, the basic unit of an OVPN service is an optical connection between a pair of CE. Membership of the OVPN is on a port-based scope, and a single port could be used to connect multiple CEs if it has multiplexing capabilities (i.e., WDM) to build an OVPN with a broad spectrum of topologies such as hub-and-spoke, full mesh, etc. Port-based OVPN service is also described as Virtual Private Cross-Connect (VPOXN), as it operates similarly to a physical optical cross-connect to the VPOXC customer. The VPOXC's port topology is defined by the customer but administered on the service providers shared platform [14]. Figure 2-1 illustrates an example of OVPN service, where VPN A customer subscribes to Gigabit Ethernet and SONET service, VPN B customer subscribes to SONET service.

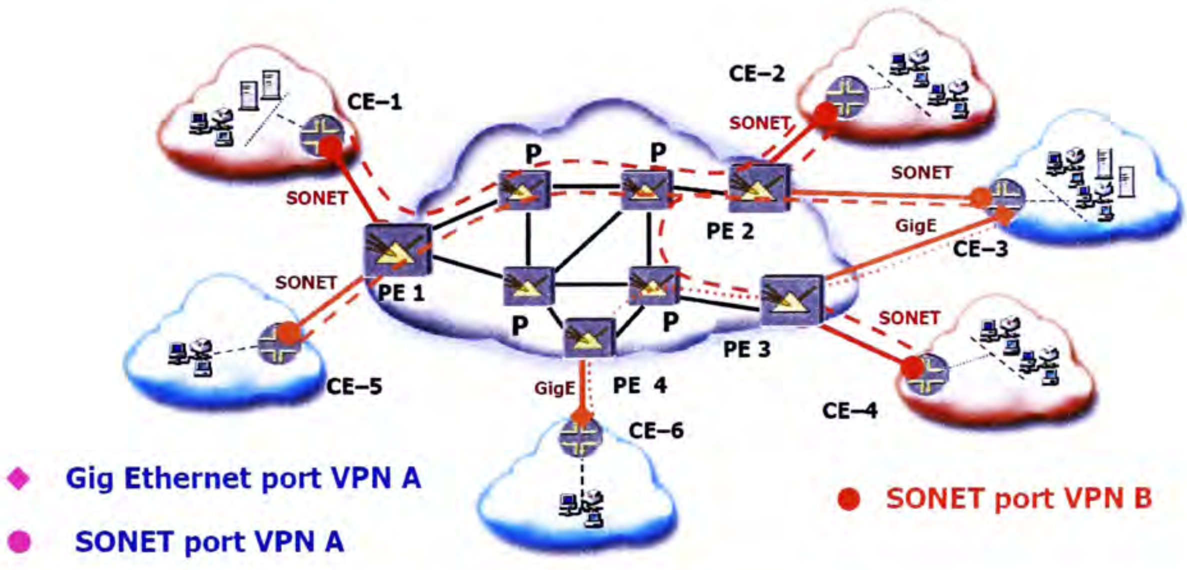

Figure 2-1 Example of OVPN service [15]

A service provider network supporting OVPN should also scale to a large number of OVPN clients. This requires each PE to allow links from multiple OVPN customers, and the PEs would exchange VPN membership information by a dynamic protocol, perhaps on an out-of-band control channel, which could also exchange security and QoS information to assist in the setup of the all-optical channel.

As with regular VPN, there could be overlapping address space among different VPN customer domains. The service provider network must be able to mask the private address space from the share network platform. In another words, the routing and addressing of the service provider network must be completely independent from the routing and addressing of the customer network. This requirement is consistent with the carrier's carrier capability as described in the IETF RFC2547bis for BGP/MPLS VPN.

In the IETF's discussion on OVPN as a provider provisioned VPN (RFC4026), it is important for OVPN to support "single end provisioning," where the addition of a new member to a particular OVPN would only involve configuration changes on the CE and its directly connected PE [16]. It is generally desirable that when a new optical connection is established or terminated between two CE, the PEs should not be reconfigured in such a way that would have service impact on existing connections. GMPLS signalling with BGP based topology discovery mechanisms would help at the control layer [17].

2.6. Reconfigurability of an All-Optical VPN

In an all-optical network, it would be the most efficient to configure the network topology and associated channel mappings to match with a given traffic requirement. However, there are usually constant changes in customer traffic requirements in a practical service provider network which makes a static efficient network unfeasible.

In the absence of wavelength conversion, a lightpath subject to wavelength-continuity constraint must use the same wavelength on an end-to-end path between two CE of an OVPN connection. The process of reconfiguration may result in service interruption of a lightpath if it is to be re-routed or shifted to another wavelength in favour of reduced blocking in the network. Reconfiguration is usually achieved using tuneable transmitters and receivers, configurable optical add-drop multiplexers and cross connects, etc.

Sometimes the benefits of reconfiguration can outweigh cost when traffic changes are quasi-static, and [7] examines the benefit of reconfiguring on shorter time scales as the resultant average packet delay. It studied two queuing models for an access network: Continuous Bandwidth Network Model (CBM) where connections between access router ports and gateway router ports as allocation of single server to N input queues;

and Wavelength Modem (WM) where each port/wavelength on the gateway router is an independent server. The study finds reconfiguration would significantly reduce average delay for a wide range of system reconfiguration interruption time intervals, especially under heavy traffic load.

Another study of reconfiguration in OVPN takes the integer programming approach to minimize average end-to-end delay while maximizing network throughput has also found an algorithm that could significantly increase the network throughput [18].

2.7. Switching Methods in All-Optical VPN

Whether a regular VPN would differ from OVPN lies on the nature of their connection that one is packet based and the other is constrained to be circuit based. Optical Packet Switching (OPS) is superior to Optical Circuit Switching (OCS) for bursty data traffic because of a higher degree of multiplexing.

Although there are some activities in the research of OPS, but it faces substantial technology hurdles in which the absence of an efficient optical buffer memory element being the most notable one [19]. Buffering would be necessary because packet networks are connectionless in nature, in which more than one packet may be destined for a particular output port in a particular moment. Packets are stored in a buffer in such case to prevent contention at the output port. Fiber delay line is the currently available solution to optical buffering, but they are bulky and provide only limited & deterministic delays [20]. The store-and-forward nature leads to fixed packet length and synchronous switching. As in traditional packet based networks, OPS may result in corrupted flows caused by out-of-order packets, delay variations, and packet loss because packets belonging to the same flow may traverse different physical paths. Consequently, massive corrupted flows may cause higher-layer protocol to misbehave.

The tight coupling of header and payload in OPS requires stringent synchronization, and fast processing and switching (ns or less). Consider a 125 bytes packet carried as lightwave transmitting at 10 Gbps would passes a network node in less than 0.1 nanoseconds. Because the response time of all-optical components are many magnitudes higher, it is easy to see that all-optical networks must take different approaches than packet routing in today's optoelectronic network.

Research in optical burst switching (OBS) targets a balance between circuit and packet switching [21]. It has the statistical multiplexing capability of OPS while avoiding the optical buffer memory and lowers other hurdles as described above. OBS utilize control packets on separate channels to reserve bandwidth resources prior to sending each burst of optical data. The bandwidth resources are released at the end of each burst. OBS separates the forwarding and the control planes and can be adopted with GMPLS to realize Labeled Optical Burst Switching (LOBS) as depicted in Figure 2-2. MPLS signaling are encapsulated in the control packets to manage the wavelength utilization among different bursts.

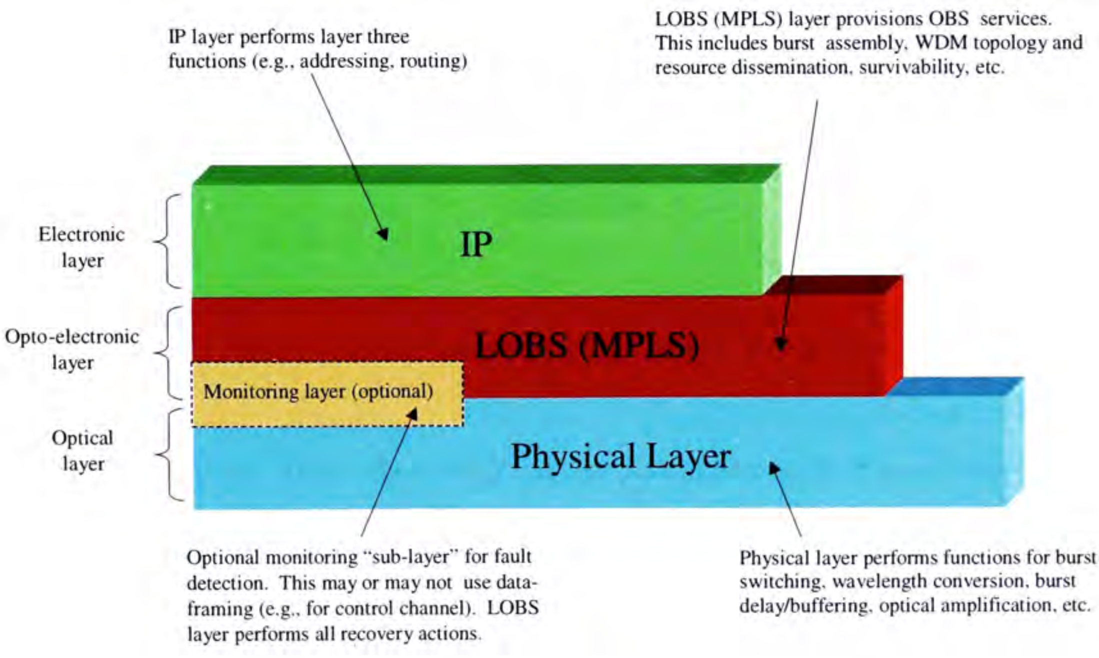

Figure 2-2 IP-over-WDM architecture based on LOBS [22]

Figure 2-3(a) illustrates a typical OPS node that uses fibre delay lines to allocate processing time for the packet header which controls the payloads switching. This is a simplified design that does not handle output port contention issues. Figure 2-3(b) illustrates a typical OBS node that sends control packets ahead of the payload by an offset time. It eliminated the use of fibre delay lines and has less stringent synchronisation requirement than OPS because of a loose coupling between the control plane and data plane.

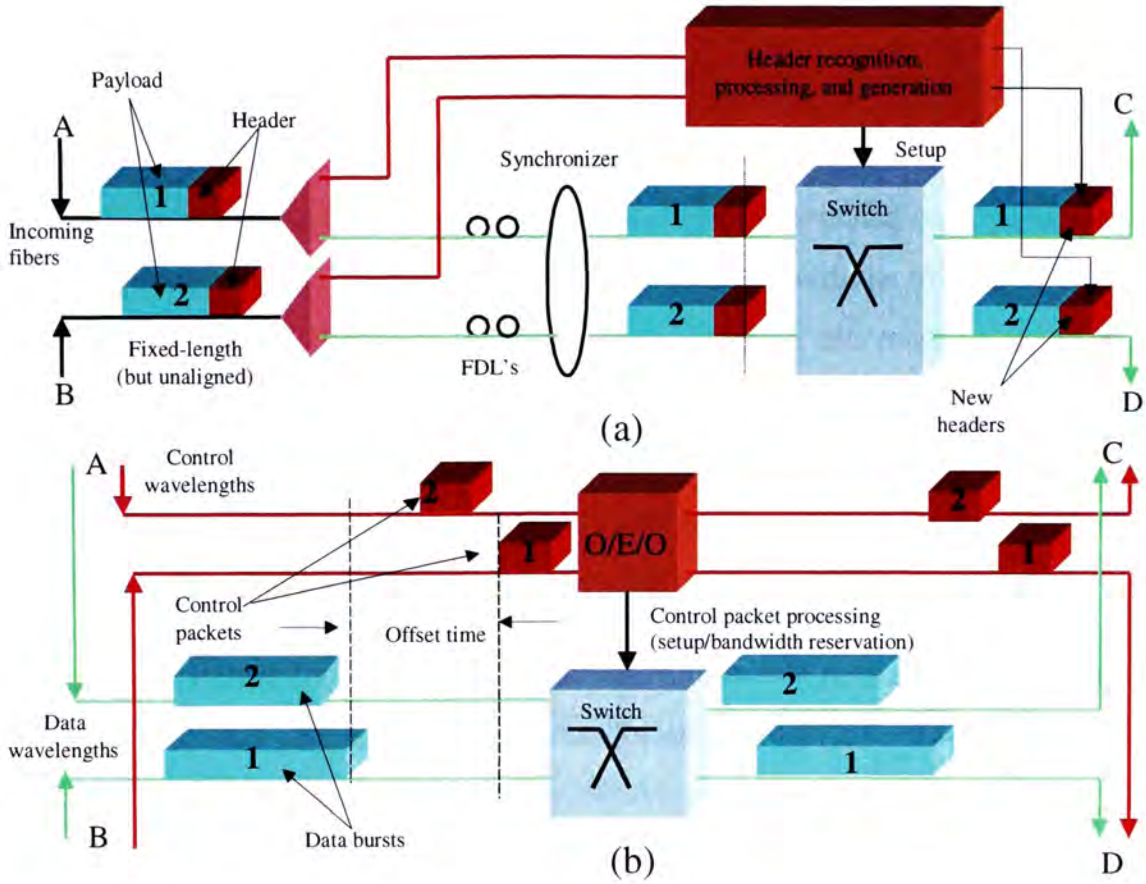

Figure 2-3 (a) Optical Packet Switching (b) Optical Burst Switching [22]

Optical Flow-routing (OFR) has emerged as an alternative to OPS and OBS [23]. A flow is defined as a set of consecutive packets in an active connection. Because OPS would result in large percent of corrupted flows especially as congestion occurs, OFR can largely reduce corrupted flows because packets of the same flow are transmitted and switched as one single identity.

When compared with OBS which uses one-way reservation protocol on a separate control channel, OFR does not rely on reservation and has the same flexibility and scalability as OPS. This is because OFR does not require the additional offset time for each burst in OBS, and it is not limited by the control channel's capacity which may increase blocking probability under heavy load.

2.8. Survivability of an All-Optical VPN

Survivability has been well-recognized as one of the most important objectives for the design of OVPNs such that any unexpected interruption upon the working traffic can be restored in a short time.

The common survivability approach in today's optical network is to allocate a 1:1 protection capacity such that the affected traffic can be switched on a protection path. It is a difficult problem to make such schemes scalable with the network size and the amount of traffic. Otherwise, the dependency between the working paths and the corresponding spare capacity in case shared protection is adopted would complicate the whole problem. A significant amount of research efforts has been addressed on the topic of achieving network survivability for general IP and WDM networks in which a single domain and uniform service requirements are assumed.

One of the solutions for the resource allocation problem in networks with OVPNs is to formulate the task into an Integer Linear Programming (ILP) model where all the traffic demands for the VPNs in the networks are jointly considered [24]. Due to computational complexity, this approach suffers from a scalability problem as the network size and the traffic demands increase. This problem is further complicated, when a single ILP is formulated, by the fact that each OVPN may address different survivability requirements.

A compromise between computation complexity and performance is desired such that the design can be applied to different network design scenarios. One commonly adopted idea is to divide the traffic demands into different protection groups as described by the $(M:N)^n$ protection architecture defined in GMPLS standard signalling protocol. A network contains n protection groups each supporting N working paths protected by M protection paths. The advantages of grouping network demands are numerous which include the improvement of scalability in computation and signalling efforts, easy manipulation of QoS and survivability metrics, and less dissemination of link-state in case a distributed control is taken.

Another survivability consideration is that today's core IP networks are increasingly connected directly to the optical layer as link speeds easily reaches STM-16 to STM-64. All-optical networks can provide millisecond link restoration in case of fibre cut, but would have no awareness in case of a router failure and would require network operators to separately consider protection against router failures. A common solution is to provision extra link capacity at IP layer to preserve QoS during traffic reroute caused by router failures, but it makes the optical layer protection seems redundant.

Optical layer protection could be designed to aid restoration from router failures as studied in [25]. The optical network would need mechanisms to detect router failure, and consider the protection lightpath's effect on higher layer routing.

Chapter 3

3. Maximizing the Utilization Of A Survivable Multi-Ring WDM Network

3.1. Introduction

The previous chapter has discussed the effects of reconfigurability, switching methods, and survivability of an OVPN. This chapter attempts to contribute by investigating methods to enhance the utilization on a survivable multi-ring WDM network that would be a typical platform to provide OVPN service.

3.2. Background

Today, service providers' optical networks often need to carry both circuit based and packet based services [26]. In a traditional ring based network, one ring is dedicated for carrying traffic while a fully redundant ring is on standby for protection purpose. This approach has been entrenched in SONET and it has become the standard configuration to offer guaranteed protection for circuit based network connection.

In a modern network however, there has been a vast increase in the amount of packet based traffic due to the expeditious growth of the Internet. Packet based traffic has been retrofitted into the existing network infrastructure for circuit based services and resulted in bandwidth deficiency. Recent development of new protocols aimed to eliminate the SONET layer for transporting packet traffics on its own ring network while maintaining protection. A successful and commercialised approach is the Resilient Packet Ring (RPR) [27] or IEEE 802.17.

The disadvantage of a traditional survivable ring network is that a protection channel must be dedicated for each working channel [28]. RPR has revoked this disadvantage by putting a healthy ring's protection bandwidth into active service until failure occurs, but its application is limited to packet based ring network.

The latest trend in networking is to exploit the optical layer for multiplying bandwidth [29]. On the optical network layer, circuit and packet based connections can coexist on the same WDM ring at different wavelengths. To provide wavelength protection on the WDM ring network is similar to providing protection on a SONET network, that a fully redundant ring is reserved for protection.

When interconnecting SONET rings, add-drop multiplexers (ADM) are relatively inexpensive and readily available. When interconnecting WDM rings, optical cross connects (OXC) and wavelength converters are typically used [30]. It is often undesirable to deploy wavelength converters because of its complexity and cost. However, the blocking probability of making a wavelength connection across WDM rings without wavelength conversion will exponentially increase as the number of ring hop increases [31]. We can relieve the bottleneck of hunting an available wavelength for connection across multiple rings by making use of the idle channels on the protection rings.

Like in the case of RPR, which uses the spatial reuse protocol (SRP) [32], the enhanced bandwidth usage is only applicable when the ring is healthy. In case of a ring failure, all the excess bandwidth usage will fall back to the basics of one wrapped ring under protection mode.

3.3. Method

The proposed heuristic method for maximizing the utilization of a survivable multi-ring WDM network without wavelength conversion relies on the fact that a network has both circuit and packet services. We define the circuit based services as an end-to-end wavelength connection between two nodes, and we assume the packet traffics are carried by RPRs on a subset of wavelengths. Layer 3 devices interconnect the RPRs for routing packets to another wavelength or another WDM ring.

Let λ_t be the number of wavelengths on a WDM ring, and λ_{RPR} be the number of wavelengths used for routing packets on RPR, then the number of wavelengths available for use by circuit based services is $\lambda_c = \lambda_t - \lambda_{RPR}$. On the protection ring, there is an equal number of wavelengths λ_{cp} to protect the λ_c circuits. Note that because of the nature of SRP, λ_{RPR} number of wavelengths is also "in-use" on the protection ring by RPR. Then, the average packet bandwidth on the WDM ring is $2 \times \lambda_{RPR} \times B$, where B is the bit rate of the RPR channel.

In the proposed method, we make the idle protection wavelengths for circuit based services, λ_{cp}, available for use. We repartition the wavelengths on both active and protection WDM rings into wavebands for protected (λ_{RPR}, λ_c', λ_{cp}') and unprotected (λ_u, λ_{up}) service. A protected circuit based wavelength connection may hunt for an available channel on either the active or protection ring's waveband, λ_c' (switch to λ_{up} in case the Active ring fails) or λ_{cp}' (switch to λ_u in case the Protection ring fails). λ_{up} and λ_u are available to provide resilient service instead of λ_{cp}, the key advantage in the new partitioning scheme is that λ_{RPR} has the option to expand into the unprotected wavelengths λ_{up} and λ_u, where it was blocked by λ_c in the original scheme. Hence the new partitioning scheme allows for resiliency to both circuit and packet based services.

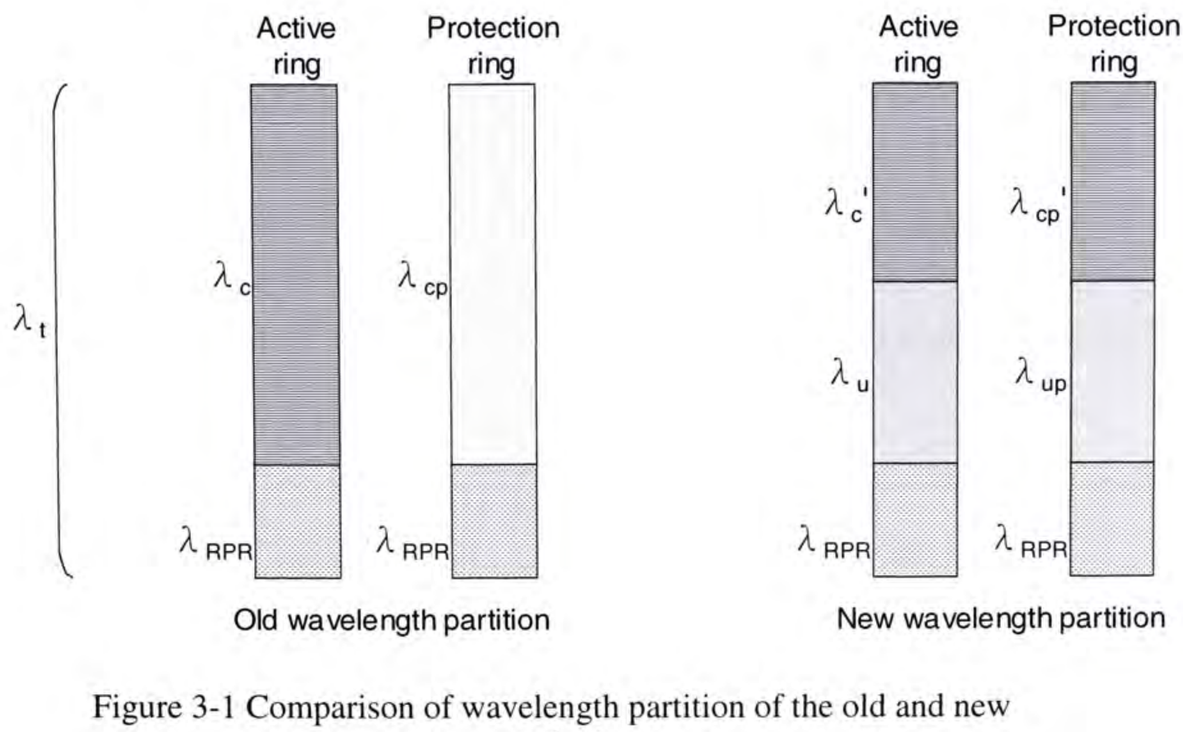

Figure 3-1 Comparison of wavelength partition of the old and new method

The limiting condition to maintain resilience and redundancy is that, the WDM ring must not support more protected wavelength connections than the number of wavelengths on a single ring, minus the minimum number of wavelengths reserved for

RPR ($\lambda_c' + \lambda_{cp}' \leq \lambda_t - \lambda_{RPR}$); and that there must not be an over subscription of QoS guaranteed packet bandwidth, B_{QoS} , on the minimum packet bandwidth under protection mode ($B_{QoS} \leq \lambda_{RPR} \times B$). This is consistent with the fact that there is only one set of working wavelengths on one ring under protection mode.

3.3.1. Effect on packet based services

Due to the excess in the number of usable unprotected wavelengths, the service provider may choose to route some packet traffic between major nodes on dedicated wavelengths as point-to-point connections. Some high priority packet traffic can also have the benefit of a dedicated point-to-point connection on the available wavelengths. This will relieve the loading on the intermediate layer three routers, and reduces the delay and jitter of the packets. The network will react better to real-time packet services such as voice over IP (VoIP) or video on demand (VOD) because of reduction in the overall congestion and delay.

Since the usage of packet bandwidth can be very flexible, the network service provider may resell a portion of the bandwidth with QoS guarantee, while the excess bandwidth are sold for best effort service only. The total amount of QoS guaranteed bandwidth on the network must meet the limiting condition. With the new method, it is possible to deploy additional RPR on the network using wavelength pairs from λ_u and λ_{up} . Traditional partitioning of wavelengths could not add RPR rings without reducing the wavelength usage on protected circuit based connections.

When the WDM ring falls into protection mode, the number of wavelengths for packet services reduces to λ_{RPR} again and all the point-to-point packet connections using λ_u and λ_{up} will fallback to RPR mode. Layer 3 routing protocols will reroute the packet traffics while the SRP fairness algorithm (SRP-fa) in RPR will manage the priority of QoS traffic and also allocate available bandwidth to the best effort traffics in a fair manner.

3.3.2. Effect on optical circuit based services

Under the new partition, there are two wavebands, λ_c' and λ_{cp}', with duplicated wavelengths available for hunting wavelength connections across the network. The greatest benefit is that it will increase the probability of finding an end-to-end available wavelength without wavelength conversion. This is shown by simulation in the following section. In effect, the result is similar to adding an overlay WDM ring to the network in place of wavelength routing to relieve blocking. In our method, we share the resource from the protection ring to gain the same benefit without increasing the overall cost and capacity of protected circuit connections.

Under the new wavelength partition scheme, unprotected wavelength connection may be handled by λ_u and λ_{up} . They also enjoy the same benefit of lowered end-to-end blocking probability as for the protected connections. The network will yield to protected circuits and drop the connections on λ_u and λ_{up} when it falls into protection mode. Nevertheless, λ_u and λ_{up} may still provide useful bandwidth on a best effort bases under normal conditions.

It is possible to gain on the number of protected circuit connection under the new method if we surrender some protection from the packet service. Normally, λ_{RPR} is provisioned to handle all normal packet traffics. Since there are ample wavelengths for unprotected traffic on the healthy ring, if the provisioning of λ_{RPR} becomes very aggressive to protect the essential QoS guaranteed packet traffic only, then some wavelengths may be shifted from λ_{RPR} to λ_c', λ_{cp}', λ_u and λ_{up} for handling additional protected services. This is feasible to do so if the network restoration time is made sufficiently short to prevent the non-guaranteed packet traffic from extended degradation.

3.4. Simulation results

We are interested to find out our method's effect on the protected circuit based connections. It is important to show that when compared with the traditional method, the new method will preserve protection while lowering the blocking probability for an arbitrary set of wavelength connections [33]. The benefit to packet based services is more qualitative and has been discussed in the previous section. Our simulations only consider the effects on circuit based wavelength connection. We used VPItransportMaker^{TM} as our simulation environment.

Simulation was done for two, three, and four WDM rings networks, each WDM ring consist of an active ring and a protection ring. The topology under simulation for the four ring network is shown in Figure 3-2. In all cases, we model each WDM ring with six nodes. There are two interconnection nodes on each ring that link with its neighbours. All nodes are attached to both the active and protection rings. For the purpose of simulation, we assumed that there are 32 wavelengths on each WDM ring.

For each network, we simulated four cases under different loading. The base case uses $\lambda_c = 32$ wavelengths on the active ring only and serves as the baseline for performance evaluation. We evaluated two cases under the new partition method without wavelength conversion. The 32 active wavelengths were split between λ_c' and λ_{cp}' over the active and protection ring in two partition ratios, 16+16 and 24+8. Their protection is guaranteed by the having $\lambda_{up} = \lambda_c'$ and $\lambda_u = \lambda_{cp}'$. A reference case was done assuming unrestricted wavelength conversion among the 32 is available at the ring interconnection nodes.

The connection demands were created by randomly selecting a pair of nodes, and each connection pair may use up to three wavelengths. VPItransportMaker's internal wavelength routing and assignment (WRA) algorithm was applied to route all the connection demands as they arrive in a random order. It may be possible to obtain better results if the WRA algorithm is optimized [34] [35].

The VPItransportMaker simulation package provides three parameters for comparison amount the different cases investigated. The network utilization index is defined as the sum of the number of wavelengths used on each network segment, where a network segment is defined as the link between two adjacent nodes. The network blocking index is defined as sum of the highest wavelength in use on each network segment. The last parameter is the network efficiency index, defined as the difference between the utilization index and blocking index.

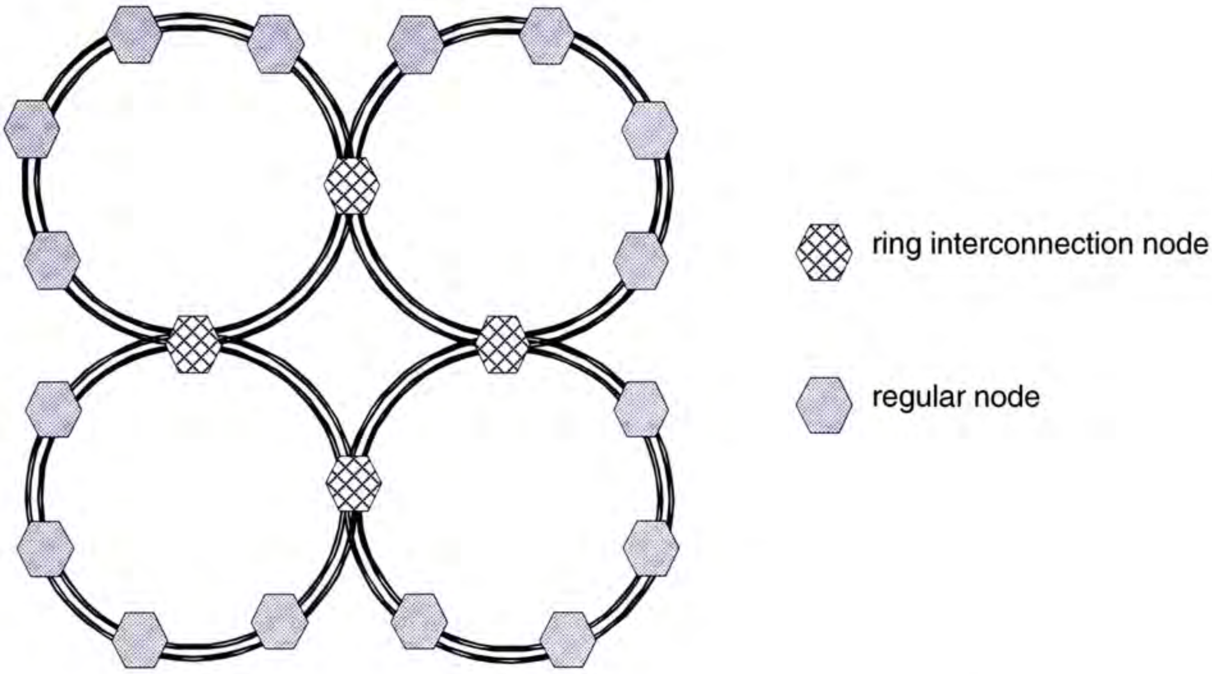

Figure 3-2 A four ring interconnected WDM ring network

Since the WRA algorithm in the simulation hunts for the end-to-end available wavelength starting from the lowest number, any gap in the allocation means that a free wavelength could not be assigned because it was not free on some segments in the connection path. When the blocking index is high, it means that the network will be more likely to block new connections. We are not interested to calculate the absolute blocking probability, the blocking index is sufficient for relative comparison amount different cases. If all nodes have unrestricted wavelength conversion capability, the utilization index and the blocking index should be identical, because there will not be any gap in the wavelength allocation table.

Only the charts for the three and four rings network simulation result are shown below for comparison. Result for the two rings network simulations is consistent with the three and four rings network and provides no additional information for interpretation, therefore it is not included here.

The comparison of network utilization index under different loading is show in Figure 3-3 and Figure 3-4. We can see that there is no significant difference in the network utilization under light connection loading. At high loading when some connections begin to block, the 16/16 partition method and the wavelength conversion solution can achieve a slightly higher utilization because there were more successful connections on the network. In the four ring utilization chart, we can see that the utilization gain begin to close again as the network saturates.

A significant observation is seen in the blocking index shown in Figure 3-5 and Figure 3-6. The new partition method consistently resulted in lower blocking than the baseline case. Using the wavelength conversion case as reference, the new method results in comparable blocking reduction and even outperform it at very high loading. We made a similar and even more apparent observation from the efficiency index shown in Figure 3-7 and Figure 3-8. Overall, the proposed method has shown potential improvement in all parameters when compared with the base case. Further more, the improvements shown were comparable or sometimes better than the wavelength conversion reference case.

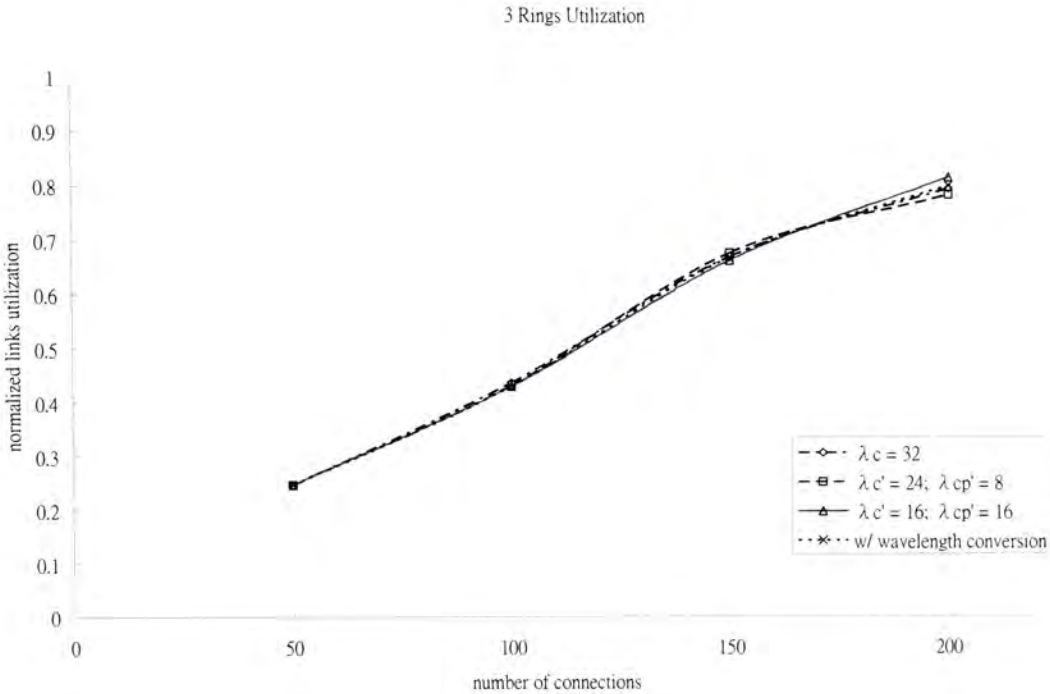

Figure 3-3 Utilization index for three ring network

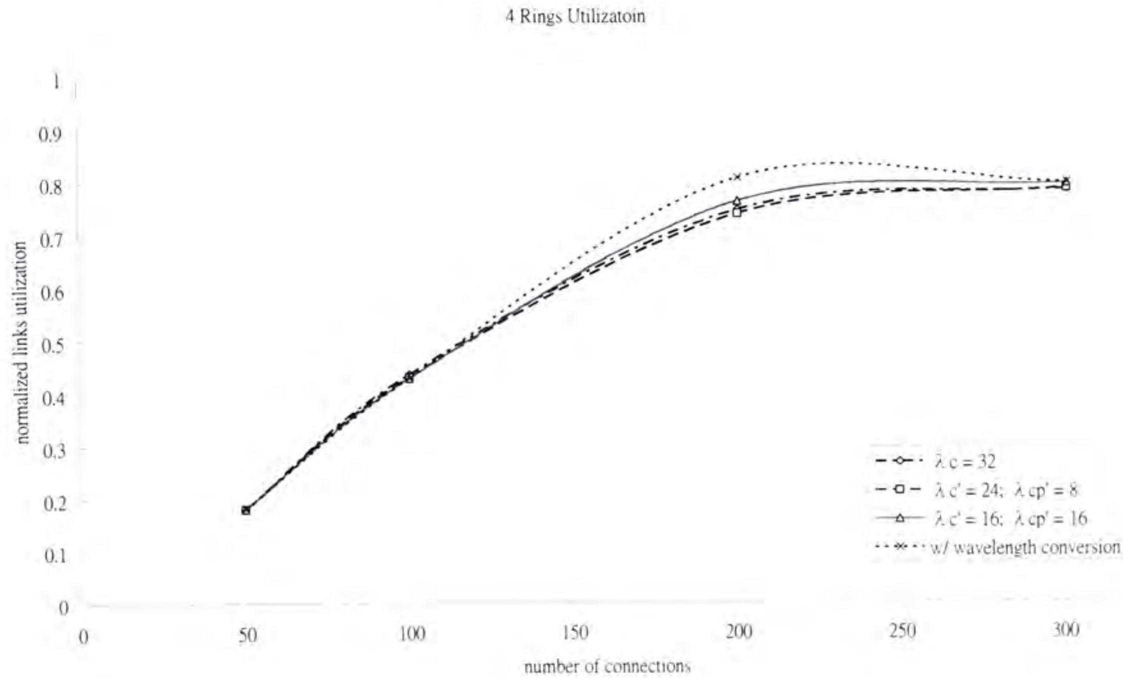

Figure 3-4 Utilization index for four ring network

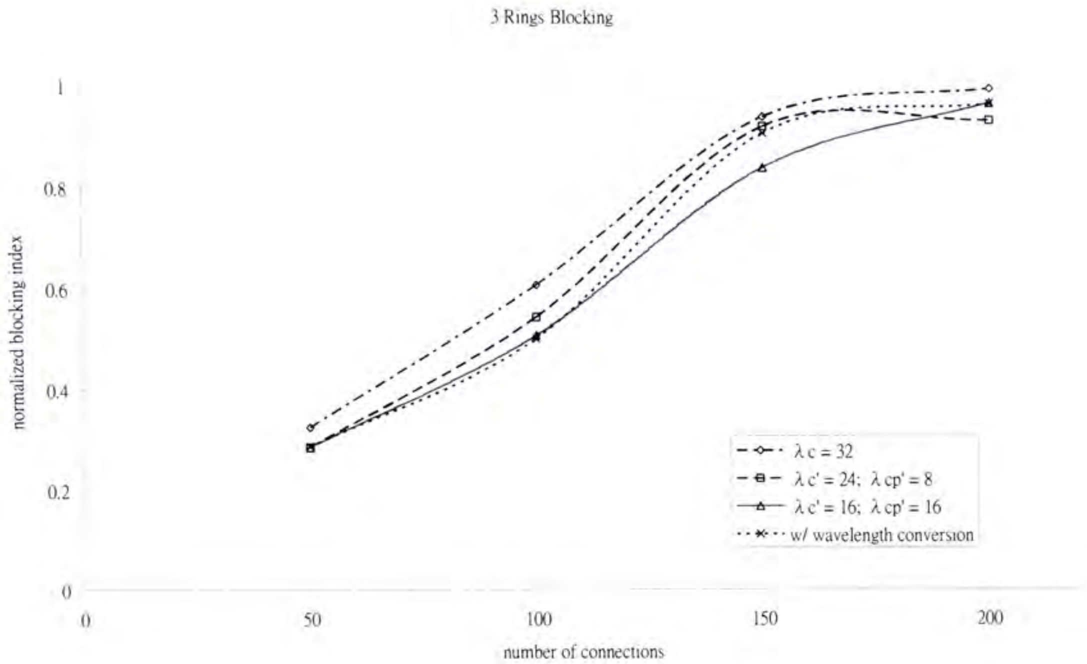

Figure 3-5 Blocking index for three ring network

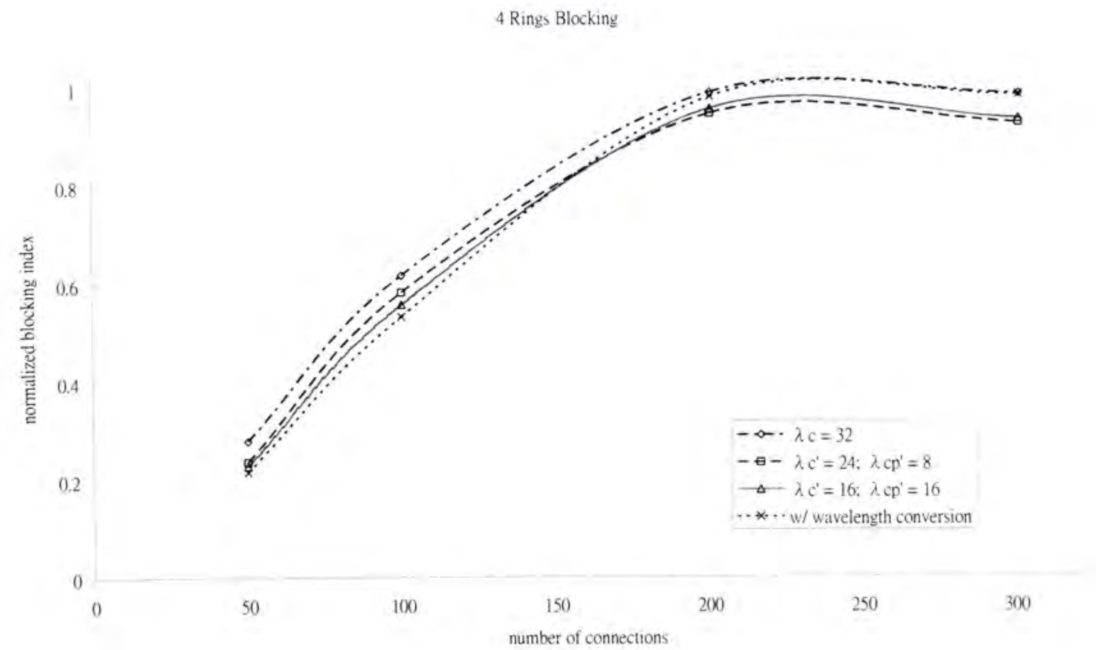

Figure 3-6 Blocking index for four ring network

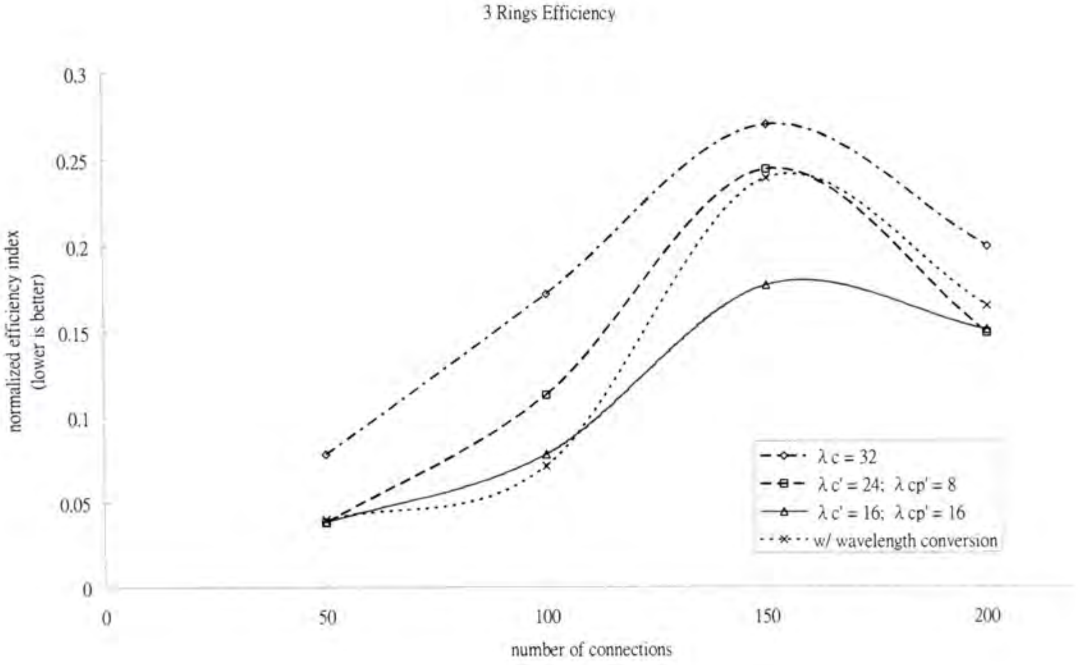

Figure 3-7 Efficiency index for three ring network

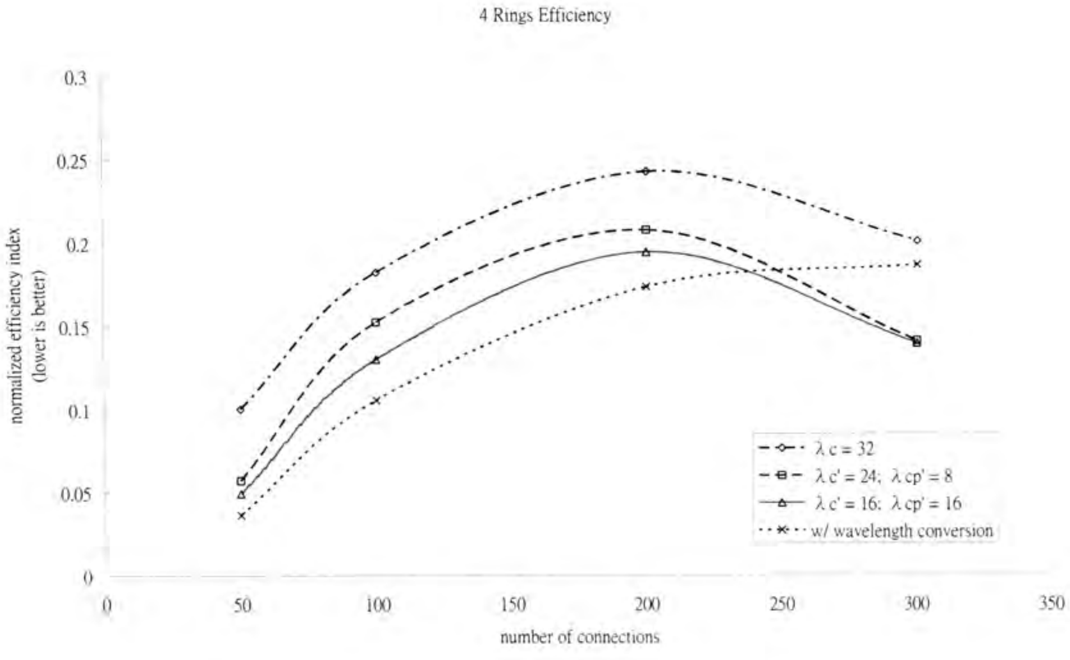

Figure 3-8 Efficiency index for four ring network

3.5. Chapter Summary

Our simulation result has demonstrated that the proposed method to repartition the wavelengths on the active and protection ring is able to make an improvement in the utilization for the protected wavelength connections due to reduced blocking. This observation is important because it is critical to show that redundancy can be maintained while we try to obtain resilience.

The most significant gain on the network utilization actually comes from the flexible use of the unprotected bandwidths. The unprotected wavelengths can be used for packet based services. Packet network protocols such as RPR with SRP-fa algorithm allows the packet connections to be compressed into fewer channels to temporarily yield protection bandwidth to critical QoS guaranteed packet traffic and protected circuit based services. By provisioning just enough protection bandwidth for QoS guaranteed packet traffic only, it is possible to gain more channels for protected circuit connections.

The proposed method benefit on the fact that today's network has a substantial amount of packet traffic. It can realize higher network utilization by jointly considering the effect of packet and optical connection services, and their protection criteria, on a multi-ring WDM network.

Chapter 4

4. Design of an All-Optical VPN Processing Engine

4.1. Introduction

In a typical OVPN, there could be a number of lightpaths shared by numerous traffic streams belonging to that OVPN. There will be times when two or more OVPNs may share a single wavelength channel, or a connection demand would use a wavelength channel exclusively. This has spawned researches in sub-wavelength routed networks and many find it to be a cost-effective and flexible way for service providers to accommodate diverse bandwidth demand from its customers [36].

Sub-wavelength routing can be done in the electrical domain with OEO conversion using Digital Cross Connect (DXC) or IP router for multiplexing. It can also be done in the all-optical domain by time division multiplexing on a wavelength channel. Traffic grooming in SONET/SDH or IP are already mature methods of sub-wavelength routing in the electrical domain and there are already sophisticated commercial hardware to accelerate its processing. Optical packet switching (OPS), optical burst switching (OBS), and optical flow routing (OFR) discussed in section 2.7 are methods of sub-wavelength routing in the optical domain, but there is not yet an efficient and adaptable optical component specialized to handle their processing.

In this chapter, we attempt to contribute by conceiving the design of an all-Optical VPN Processing Engine (OVPN PE). Our effort will focus on a conceptual design based on known properties of optical elements. We will assume such elements to function under ideal conditions and we do not consider any cost issues. We seek to overcome a common problem in today's OVPN solution, which relies on OEO conversion for VPN processing and routing. The objective of the all-optical VPN processing engine would relieve the OEO bottleneck and let OVPN to achieve the potential bandwidth of an all-optical network.

4.2. Concepts of Optical Processors

Previous studies on optical processors were mostly focused on a specific function of an optical component for optical signal processing as spectral filtering functions. This class of optical processing device (OPD) is described by their transfer function as illustrated in Figure 4-1. OPD applies a dynamically reprogrammable complex-valued spectral transfer function to an input signal. The range and types of spectral transfer function that an OPD can be configured to perform is determined by its physical characteristics [37]. One example application would be to program the OPD to auto-correlate against a specific optical packet pattern to decode it without electronic processing or for making routing decisions.

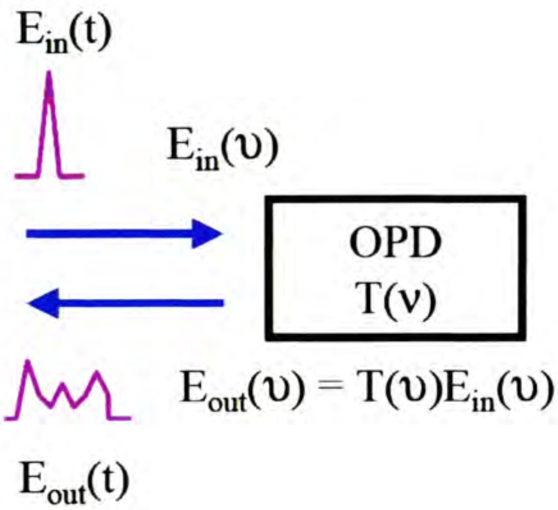

Figure 4-1 Optical processor defined by a transfer function

One optical processor that would fit the above characteristics could be fabricated by composite fibre Bragg gratings (FBG) as illustrated in Figure 4-2. It has found potential application in spectral phase encoding and decoding in Optical CDMA [38][39]. The programming of codes may be incorporated in the device by placing an electro-optic phase modulator between the encoding gratings to shift the relative phases between the temporally dispersed spectral components in a controlled manner.

Figure 4-2 Fibre grating optical processor

The schematic of a spectral phase encoder/decoder is shown in Figure 4-3. The device consists of a pair of step chirped FBGs arranged in series. Spectral codes can be programmed by varying the reflectivity of the respective wavelength selective grating subsections. When an input lightwave is incident on the first chirped grating, the wavelengths are dispersed in time and the reflected pulse is temporally expanded (coded). When this expanded lightwave is reflected from a second FBG having an opposite dispersion slope, the wavelength components are resynchronised and the original lightwave is reconstituted (decoded).

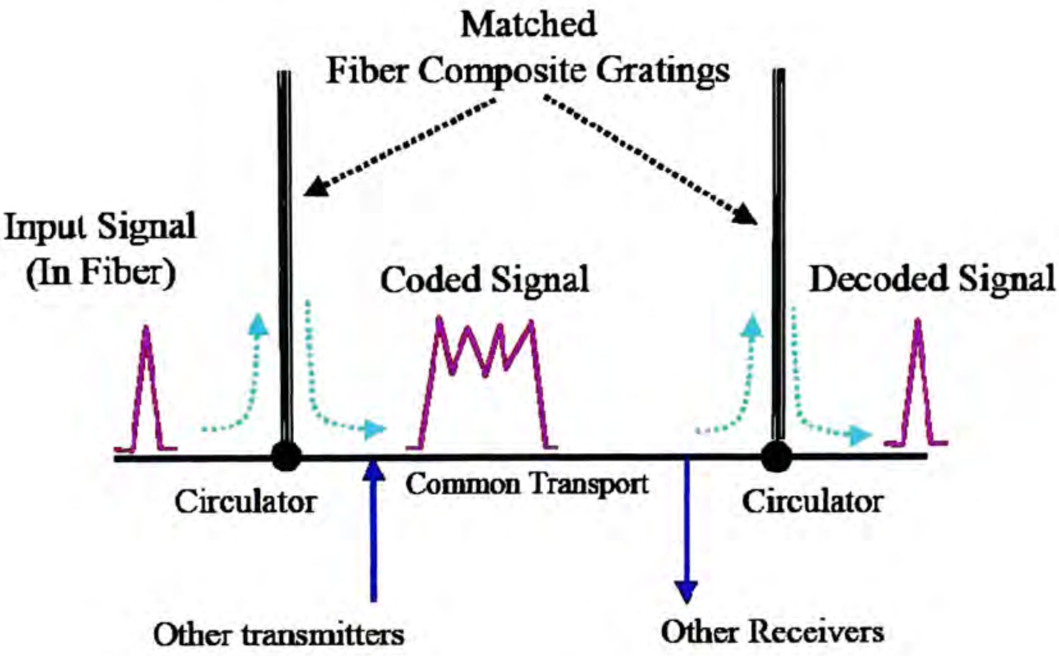

Figure 4-3 Fibre composite gratings coding/decoding [39]

There are other studies on optical processors on the broader scope of optical computing, which may incorporate advanced architectures such as optical array logic, parallel processing, and heterogeneous processing [40]. However, this class of optical processor does not have direct application on all-optical networking because its purpose is to compute arithmetic results.

There are also research to integrate photonics and electronics to combine their capabilities and allow creative VLSI engineer to construct entirely new architectures and applications with dramatic advantages over today's systems [41]. An example is a novel programmable device based on FPGA that incorporates multi-technology which includes digital logic, photonic, MEME, CMOS based analog, etc. [42]

4.3. Design Principles of the All-Optical VPN Processing Engine

Network Processor (NP) is a popular element in today's core network equipment. NP can be defined as a programmable device with architecture features designed for application specific packet processing. It has evolved from the classical reconfigurable devices such as Field Programmable Gate Array (FPGA) and high performance non-reconfigurable Application Specific Integrated Circuit (ASIC) because of rapid developments in lower layer network protocols and new demands from upper layer applications. NP combines the high-performance of ASIC with the programmable flexibility of FPGA with customization in networking applications.

Optical burst switches may also benefit from using electronic NP to process signalling information, given that the signalling channel is out-of-band and goes through OEO conversion. An electronic message engine specialized for OBS application has been evaluated with respect to Just-in-Time (JIT) signalling in [43] as an example of NP application in optical networking.

Similar to the NP used in the modern packet switches and routers, our design of the OVPN PE is conceived as a programmable optical device to provide versatility in optical signal processing aimed at OVPN application requirements

The architectures for most NP consist of multiple processing elements arranged in a pipeline or array configuration. This is because a packet would typically go through multiple stages of processing controlled by various network protocols and a NP should be capable of handling multiple input and output ports. Traditional electronic NP would leverage parallel processing to achieve higher data rates and shorten latency, but that is unnecessary in all-optical processing because everything goes at the speed of light. However, the OVPN PE would still need to maintain parallel processing capability to handle multiple I/O ports simultaneously because of the lack of feasible optical memory element.

4.3.1. Systolic System

We adopted a systolic system [44] as the architecture of our all-optical VPN processing engine. A systolic system is an array of interconnected cells arranged in any regular structure as illustrated in Figure 4-4. Each cell in the system is capable of performing some simple operation as the objective is to simplify design and implementation. Cells in a systolic system interconnect in a pipelined fashion to its nearest neighbour and only boundary cells would interact with external components as I/O ports. Such a system is named "systolic" because it allows a stream of data (electrical or optical) to flow through at a regular rate analogous to that of a pumping heart.

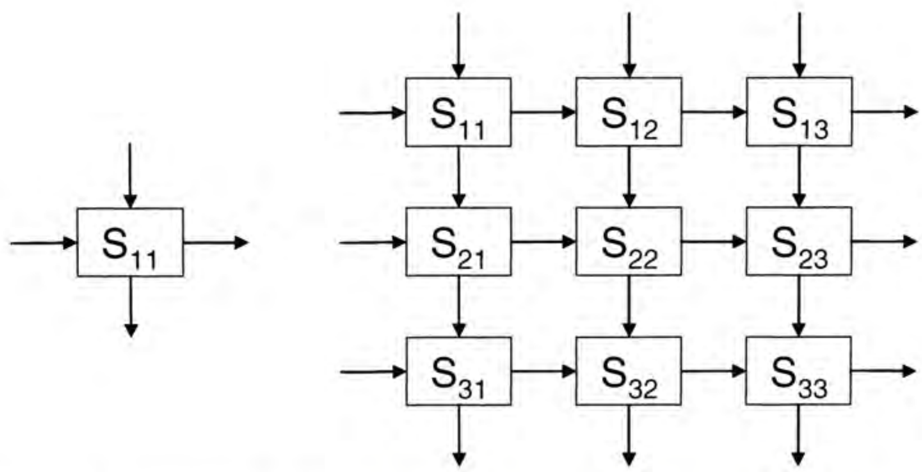

Figure 4-4 Illustration of a simple systolic system (right), and a single cell from the array (left)

One design assumption of our all-optical VPN processing engine is that simple and regular interconnections would lead to inexpensive implementations and high densities, as it has been validated by the semiconductor industry. High density is also a key enabler for high performance. For these reasons, we are interested in designing processing elements that have simple and regular data flows. We are also interested in using pipelining in hardware implementation because processing may proceed concurrently with input and output which minimized the need for optical delay element.

4.3.2. Design Considerations of an Optical Processing Cell

Using a systolic system as the bases of our OVPN PE's architecture, it would comprise an array of identical optical processing "cells." Each cell would contain some basic programmable optical processing elements. An input signal to the OVPN PE would go through multiple stages (cells) of processing to reach a desired state at the output.

In respect to OVPN application, the following capabilities would be desirable in a processing element:

1. An optical filter to enable or disable a particular port to control OVPN membership.
2. Optical add/drop multiplexer (OADM) for wavelength grooming
3. Wavelength conversion for channel remapping
4. Optical signal amplification and regeneration
5. Signal modulation for optical labelling
6. Signal encoding/decoding for encryption/decryption

In deciding the components of an OVPN PE cell, it would be advantageous to select optoelectronic components that can be implemented as planar lightwave circuit (PLC) because they can be fabricated on a substrate using VLSI technologies. It should also be possible to arrange them in a systolic array as described in section 4.3.1.

4.3.2.1. Mach-Zehnder Structures

Mach-Zehnder (MZ) structure is a very versatile optical component that can be fabricated as planar lightwave circuits (PLC) and it fits very well with our design requirement. Cascaded Mach-Zehnder interferometers have been proposed for a variety of optical signal processing functions including but not limited to the list below [47]:

- Optical switch (cross/bar states)
- Optical filter
- Dynamic gain equalization filter
- Wavelength add-drop mux/demux
- Wavelength conversion
- External modulator

The function of a Mach-Zehnder structure is often complemented with other optoelectronics elements built on the same substrate. A typical adaptation on an MZ structure is to introduce a thermo-optic or electro-optic induced phase shifter on each arm to produce the interferometric effect. Also, diffractive property may be induced in the MZ interferometric structure by overlaying it with an acoustic transducer [48].

Planer waveguides can be fabricated from different materials including silica (i.e., glass), polymer (i.e., plastic), silicon (Si), indium phosphide (InP), and lithium niobate ($LiNbO_3$) [49]. The choice of materials will effect the waveguides cost, reliability, dimension, propagation loss, power consumption, electro-optic and thermo-optic coefficient, etc.

4.3.2.2. Vertical Cavity Semiconductor Optical Amplifier

Another versatile optoelectronic component often used in all-optical signal processing is semiconductor optical amplifier (SOA). For the design of our OVPN PE, we will consider a special class of SOA known as the Vertical Cavity Semiconductor Optical Amplifier (VCSOA), which is also a Vertical-Cavity Surface-Emitting Laser (VCSEL) operated below threshold. VCSEL can be made as a tuneable source.

VCSOA provides a unique characteristic to be fabricated on silicon substrate as a two-dimensional array and is suitable to integrate with other PLC on the same silicon wafer. These properties are important given our choice of systolic array for our OVPN PE architecture. VCSOA also has other advantages over tradition SOA because it is polarization insensitive and offers high coupling coefficient in a planar structure, which results in a low noise figure. Using VCSOA as switch or modulators has the added advantage to provide transmission gain to compensate for coupling loss which predicts cascadability of over 100 stages [50].

Potential applications for the VCSOA/VCSEL includes but not limited to the list below [51]:

- Preamplifier
- Optical interconnect
- Optical switch (on/off states)
- Wavelength conversion
- Modulation
- Tuneable light source

The research in vertical cavity devices has been a topic with increasing interest. Novel designs and new applications are regularly uncovered. We consider only the theoretical functions of such devices in this thesis and attempt to apply them to our OVPN PE design without contemplating on their layer structure.

4.3.2.3. The Optical Processing Cell

We propose a novel design of an optical processing cell for our OVPN PE based on the above considerations on versatile PLC components as illustrated in Figure 4-5. Each cell is composed of two acousto-optic MZ tuneable filters and two MZ interferometers with phase shifters on each arm, bridged by VCSOA. Because VCSOA is fabricated vertically on the substrate, a lightwave going from the planar waveguide onto the VCSOA may be bent by mirror [52] or polymers [53] fabricated on the same substrate. There is also research on vertical cavity photonic integrated circuits [54] which can make transverse coupling between the vertical cavity elements. In reality, there may be more intricate issues on the practical fabrication of such a device but it is outside of the scope of this thesis to seek a feasible fabrication method.

The optical processing cell in Figure 4-5 has four sets of interface {a, a'} {b, b'} {c, d'} {d, d'}, there is also cascading interface x and y. A port can function as input and/our output depending the direction of the travelling lightwave and its interaction with each element in the cell. Each cell has the potential to function as an optical filter, mux/demux, modulator, wavelength conversion, amplifier, etc.

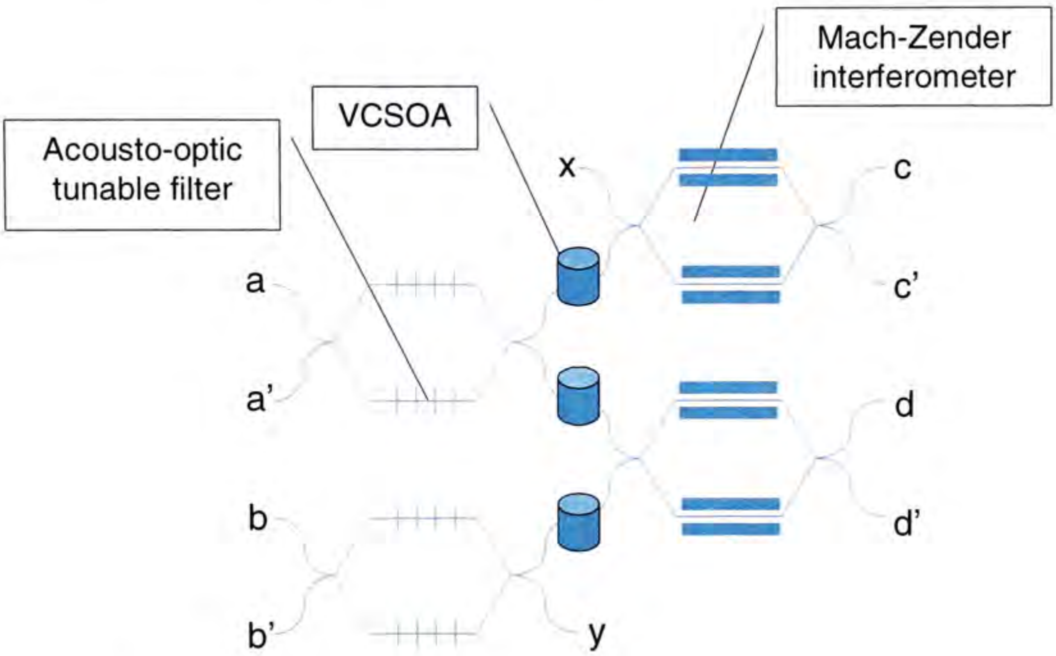

Figure 4-5 Novel design of an optical processing cell

Consider the case if a cell is to function as an optical encoder by the principle of operation shown in Figure 4-3. The composite gratings to encode a signal can be programmed in the optical processing cell by the acousto-optic tuneable filter. As illustrated in Figure 4-6, an input signal from port *a* is reflected by the gratings as an encoded signal, it is then feedback into the system via port *b* for downstream processing.

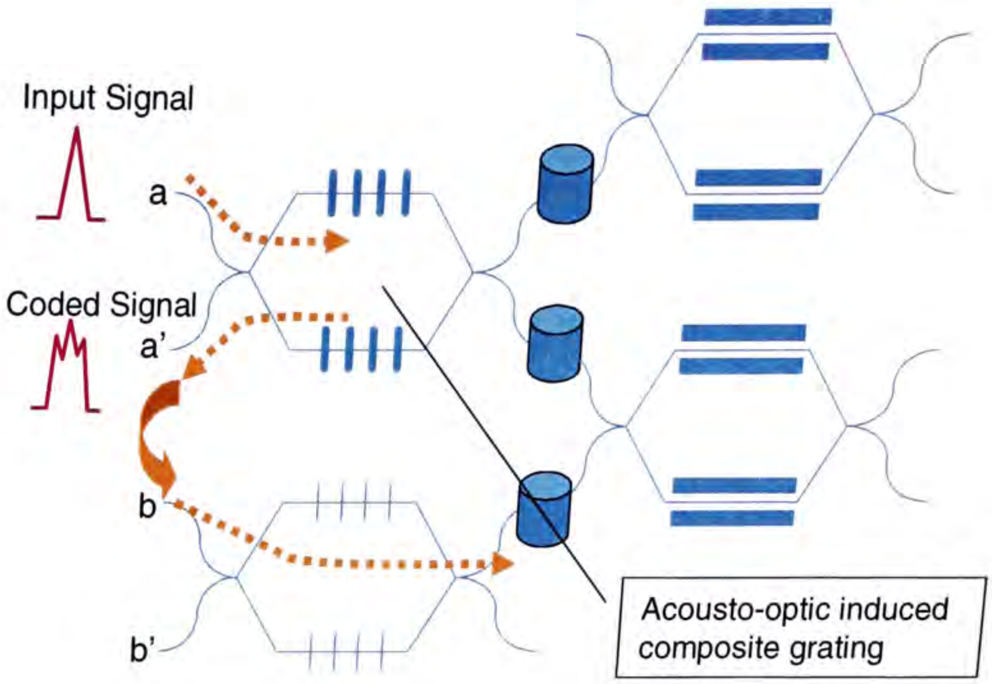

Figure 4-6 Signal encoding by acousto-optic induced composite gratings in optical processing cell

Consider another case when the cell functions as a wavelength converter by cross-phase modulation (XPM). The typical configuration of a wavelength converter with MZ interferometer and SOA is shown in Figure 4-7. In principle, a continuous-wave (CW) at wavelength λ_i is injected at the input and it will be modulated by the phase shift through the SOA caused by an original input signal at wavelength λ_i . A wavelength converted signal is obtained at the output by filtering out λ_c .

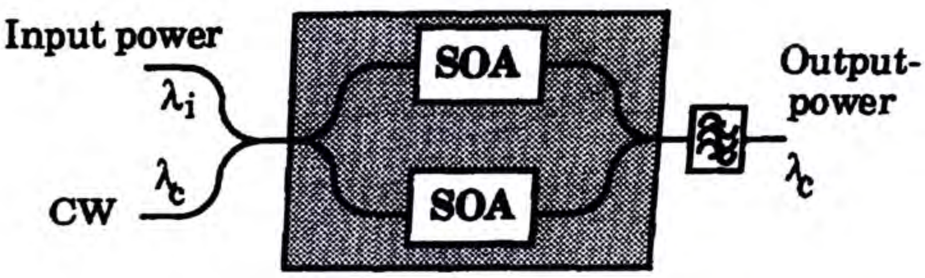

Figure 4-7 Schematic of SOA MZ Interferometer wavelength converter [55]

Mapping the above wavelength conversion configuration of Figure 4-7 to the optical processing cell, we obtain a two-stage arrangement shown in Figure 4-8. Signal λ_i and CW λ_c is feed into one set of input on the first cell, the diffractive filter is made inactive and the combined input is split into two arms with VCSOA where XPM will take place causing the wavelength conversion process. The wavelength converted output λ_c is acquired when λ_i is filtered by the diffractive filter at the second stage. Optionally, the CW λ_c may be generated by one of the VCSOA functioning as VCSEL at a preceding stage to make the whole function less dependent on external sources.

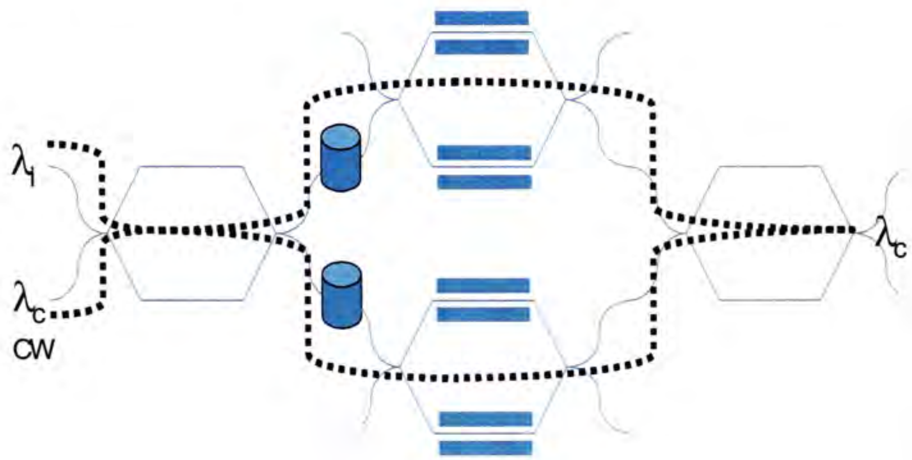

Figure 4-8 Schematic of wavelength conversion with two optical processing cells

It should also be noted that a single optical cell may perform multifunction simultaneously given that there is no contention on the element resources. Multifunction may be performed on the same optical stream or on multiple streams crossing over on the same cell. For example, signal encoding and wavelength conversion illustrated in Figure 4-6 and Figure 4-8 can be perform by the same cell on a single optical stream.

4.3.3. All-Optical VPN Processing Engine

Consistent with the architecture of a systolic system described in section 4.3.1, the OVPN PE is formed by interconnections of the optical processing cells of Figure 4-5. Layout of a sample OVPN PE with 3 x 3 cells is shown in Figure 4-9. With the larger structure, it is expected that more complicated functions can be superimposed and that multiple input and output can be processed simultaneously.

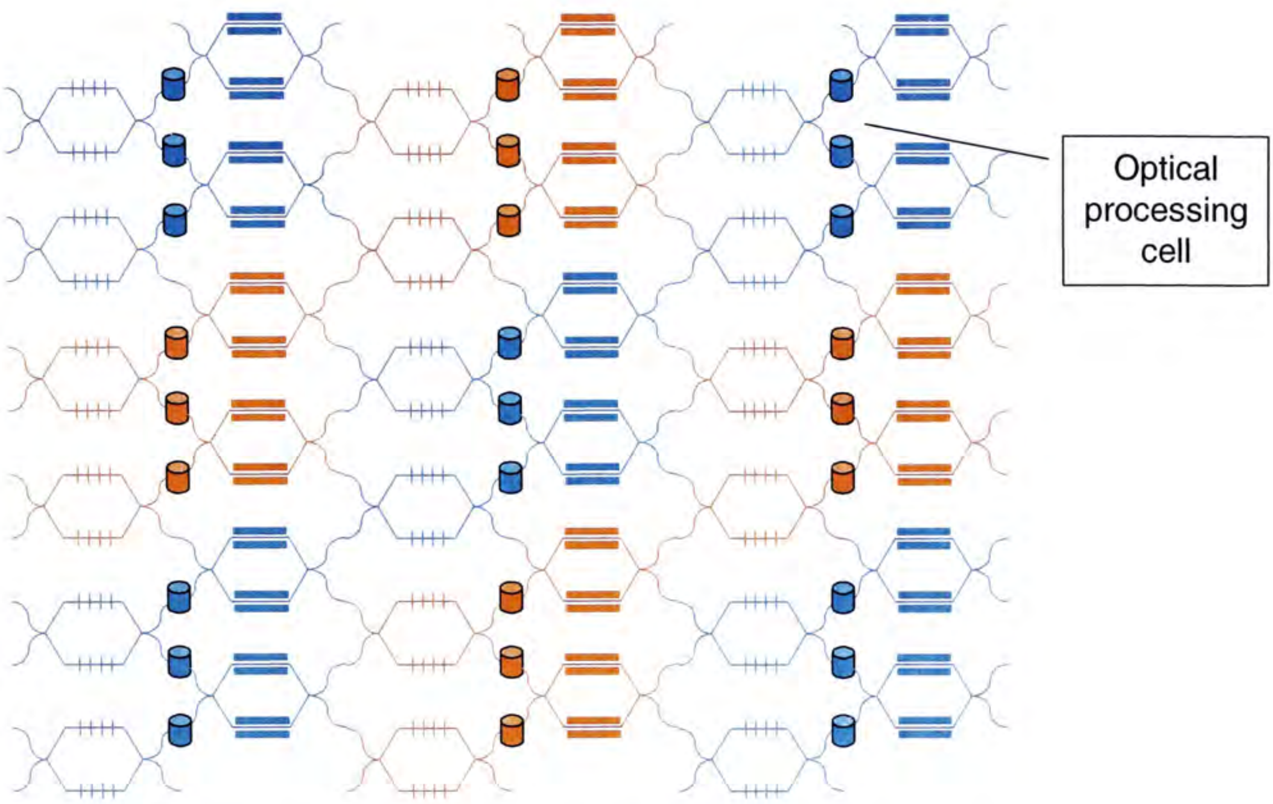

Figure 4-9 Layout of a 3 x 3 OVPN Processing Engine

Consider the four-channel wavelength multiplexer of Figure 4-10. If we superimpose the required MZ interferometers on to an OVPN PE similar to that of Figure 4-9, we would get a mapping shown in Figure 4-11 with 2 x 2 cells. This principle can be extended to other functions that utilize MZ and SOA, such as an OTDM add-drop multiplexer, SOA-based 3R regenerator, etc.

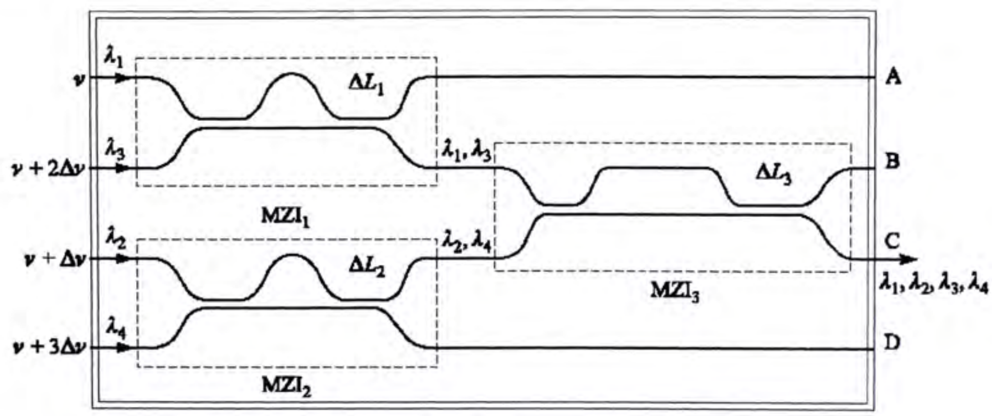

Figure 4-10 Four-channel wavelength multiplexer [56]

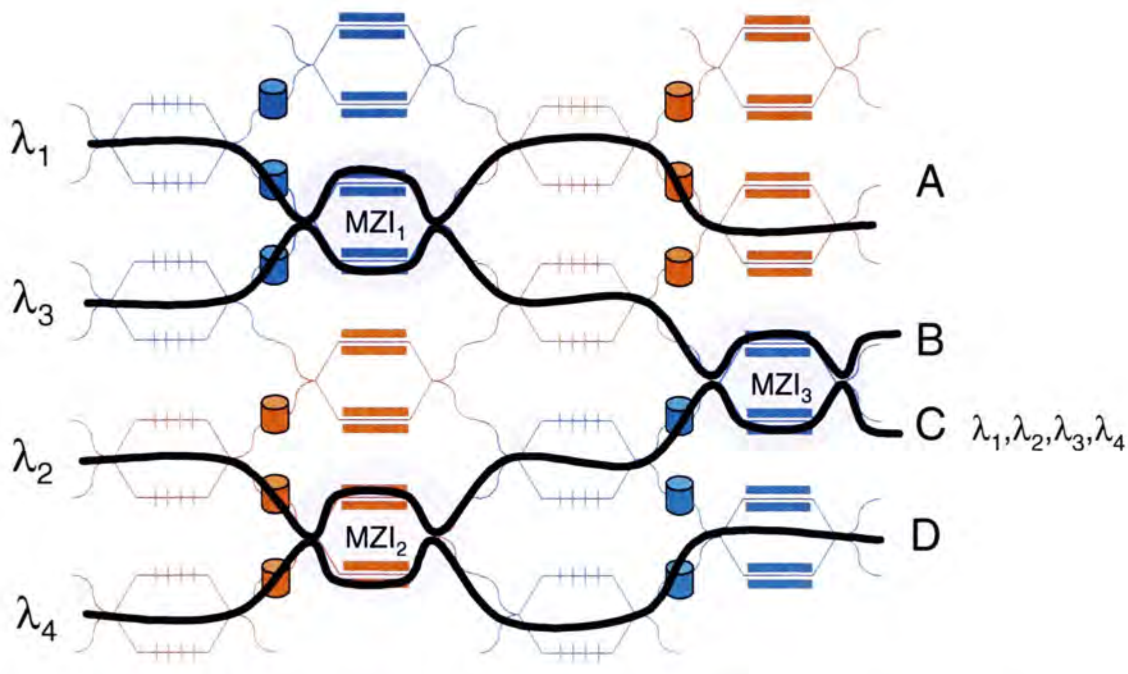

Figure 4-11 Mapping of four-channel wavelength multiplex function on an OVPN PE with 2 x 2 cells

4.4. Design Evaluation

All the elements selected to integrate in the OVPN PE have already been proven to provide suitable optical bandwidth in the telecommunication wavelength band of 1.3μm and 1.55μm. Performance of the OVPN PE may be estimated by the typical switching time of its elements:

Acousto-optic filter: 10μs with nominal tuning rage of 145nm [57]

MZ interferometer: 1ms (thermo-optic), 50ns (electro-optic) [57]

VCSOA: 10ps [58]

A thermo-optic MZ interferometer is the candidate for performance bottleneck in our OVPN PE design. This can be easily overcome by choosing waveguide materials suitable for electro-optic application. Hence, it is undesirable to use silica waveguide because of its amorphous and centro-symmetric property which results in poor response to electro-optic effects. In contrast with silica, lithium niobate ($LiNbO_3$) has high linear electro-optic coefficients due to its acentric property and it also has low propagation loss in the telecommunications band. In addition, the acousto-optic filter is typically fabricated on $LiNbO_3$ [48], this makes $LiNbO_3$ the waveguide material of our choice.

Scalability of a single OVPN PE is practically limited by the fabrication technology of the substrate. Since VCSOA inside the optical processing cells can provide integrated gains on the signal path, path loss would not be the bottleneck of scalability. Hence the dimension of an OVPN PE could be expanded by cascading multiple packages of OVPN PE externally. Further consideration on expandability is given to the north and south boundary of the systolic array (port x and y of Figure 4-5). A transitive closure could be made between the north and south boundaries to optimize the wavelength routing distance between the input and output ports.

4.5. Application Example

Application of the OVPN PE is positioned at the edge device of a photonic MPLS network as illustrated in Figure 4-12. As with other photonic integrated circuits, it aims to reduce complex optical circuits to a single substrate and allow efficient multi-channel operations to be realized.

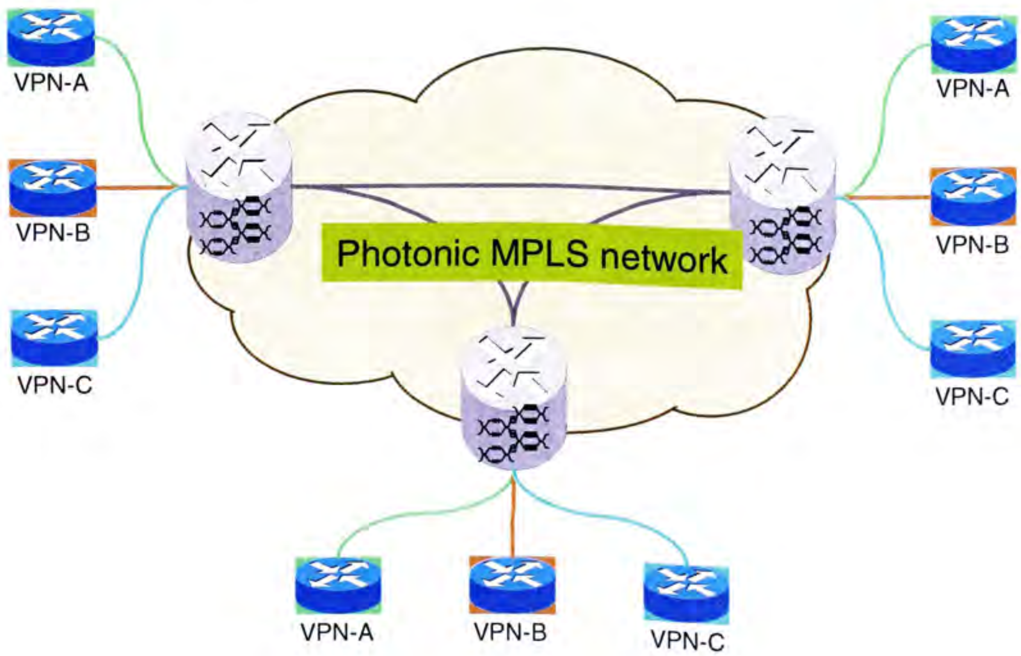

Figure 4-12 Model of a photonic MPLS network

The OVPN PE is designed with the potential to handle the following typical functions at the OVPN edge:

- Optical label processing
- Optical add/drop multiplexer
- Conditional wavelength conversion
- Port based security filters
- Traffic encoding/decoding

There are active researches in photonic MPLS routers based on discrete optical components to integrate IP and photonic networks. One example is shown in Figure 4-13. We may use OVPN PE to integrate the optical processing elements seen in Figure 4-13 to a single substrate. Figure 4-14 offers a heuristic functional block layout for reference.

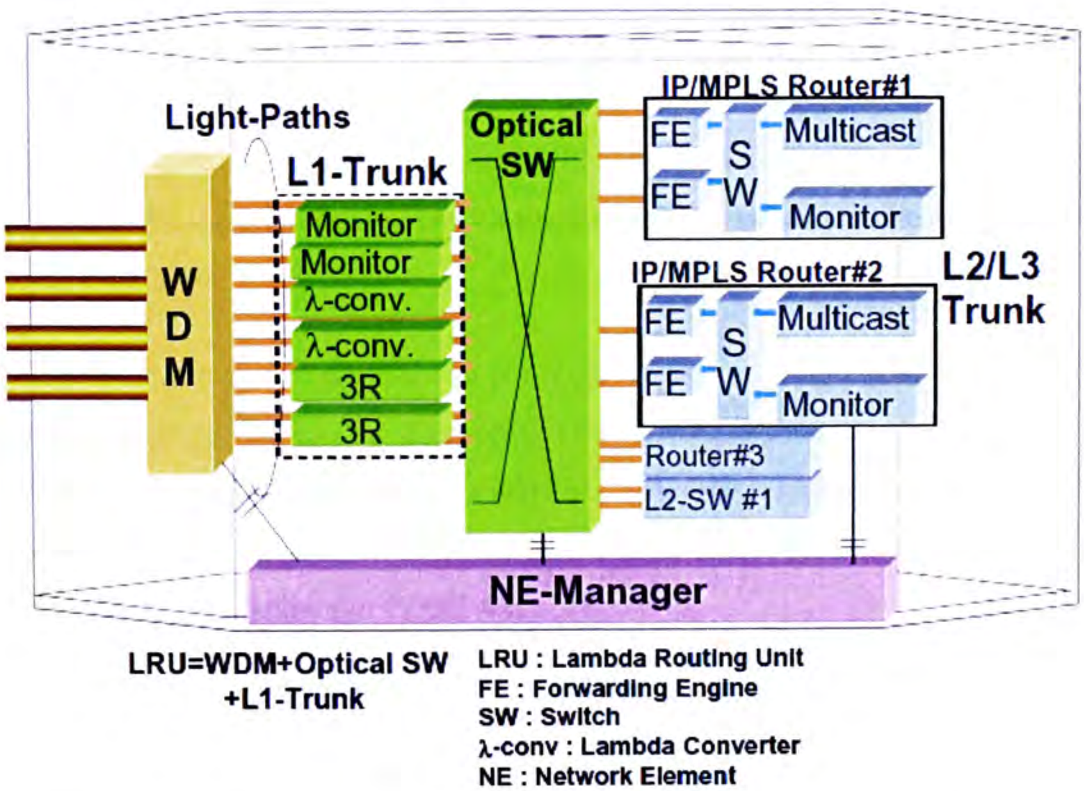

Figure 4-13 Functional configuration of NTT's HIKARI router for photonic MPLS [59]

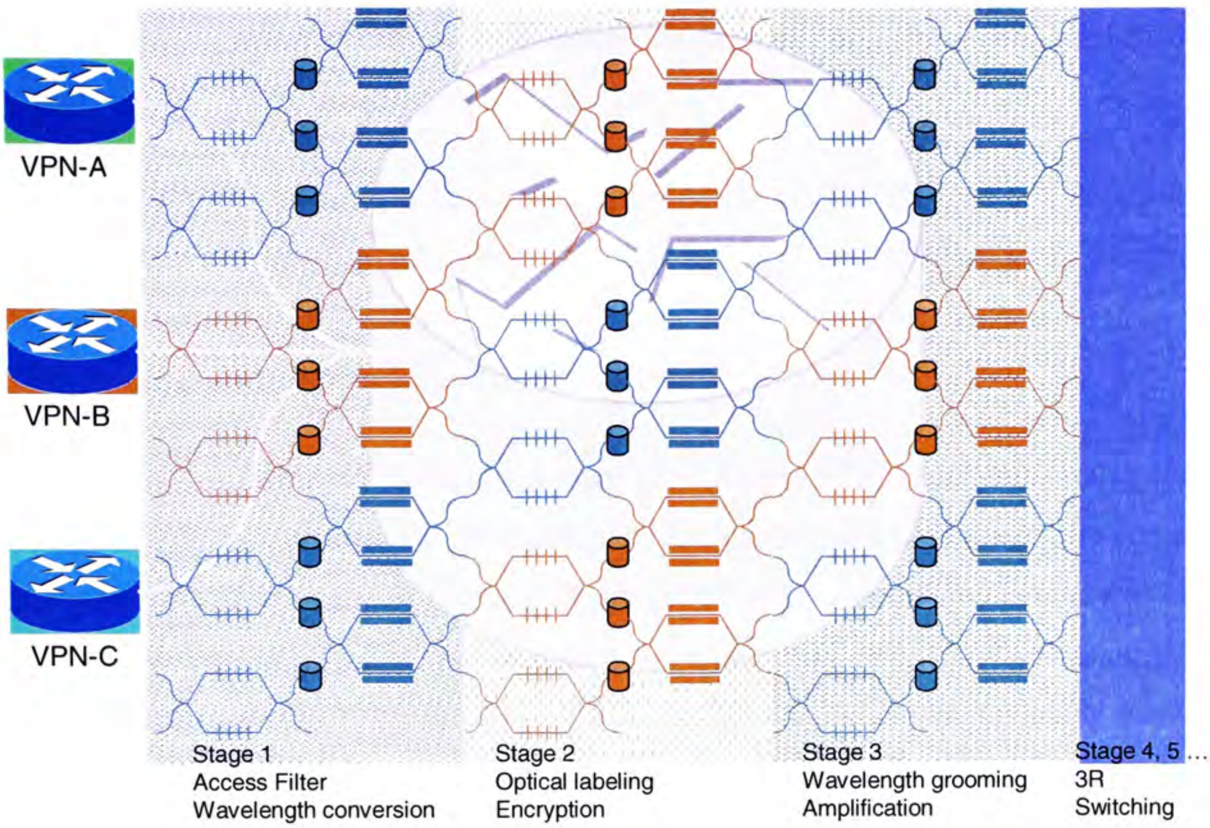

Figure 4-14 Heuristic functional block arrangement of an OVPN PE inside a photonic MPLS router

In the above figure, VPN-A, VPN-B, and VPN-C represent the CE routers connecting to the OVPN Processing Engine empowered PE router similar to the VPN reference model in Figure 1-5.

The OVPN PE can enable or disable a port connecting to a VPN client by the acousto-optic filter in stage one to exercise access control. At the same time, the lightwave coming from the VPN client may convert to a different wavelength according to the channel utilization inside the service provider network. This can be done by the schematic previously shown in Figure 4-8.

In stage two, encoding of the lightwave may be desirable to keep the clients lightpath private and it can be done by the schematic previously shown in Figure 4-6.

In stage three, it is probably necessary to do wavelength grooming, as previously shown in Figure 4-11, for lightwaves coming from different clients and select their exit ports according to their next hop destinations. It may also be necessary to amplify the signals by the VCSOA for further transmission.

Other possibilities of all-optical processing inside the OVPN PE are open depending on the available on-chip resources. Similar to VLSI technology, more complex functions will become possible as the array gets larger. Further work is to be done to explore more potential capabilities of the OVPN PE.

As discussed in Section 2.2, most commercially available OVPN systems today uses OEO conversion to process the data stream in the electrical domain by software control, compare with all-optical processing with our OVPN PE. The only exception that can be seen in the near future is Intellambda's ILS640 system. ILS640 claims to intelligently aggregate network traffic flows onto DWDM wavelengths using full C-band tuneable lasers, which are then switched by a modular, non-blocking, all-optical wavelength switch fabric that is incrementally scalable from 4 wavelengths to 320 wavelengths.

At the present time (October 2005), the ILS640 system is not commercially available, nor publicly seen. Only a proof of concept demo was offered at SUPERCOMM 2005 in an off-site private environment. According to product intelligence from the press community, ILS640 uses an architecture based on off-the-self components, with secret intellectual property that gives them a competitive advantage.

In contrast with our OVPN PE, which is an integrated programmable optical processor yet to determine its feasibility for production, the ILS640 seems to address similar features with discrete components using today's technology. Hypothetically speaking, it is possible that our OVPN PE could replace the core components in the ILS640 to make the system more versatile and achieve higher port density.

4.6. Chapter Summary

Concepts of optical processors were studied in this chapter and the principles behind the design of an all-optical VPN processing engine had been presented. Our design was conceptual in nature and was based on known properties of optical elements. We assumed such elements to function under ideal conditions and had not considered any cost issues. The result is a planar lightwave circuit based structure integrated with acousto-optic tuneable filter, Mach-Zehnder interferometers, and vertical cavity semiconductor optical amplifiers. Devices made with this design may be compatible with VLSI low-cost manufacturing in a small and reliable package to provide programmable functions targeted at OVPN applications on a single device. We hope this device concept may lead to substantial new capability in next-generation communication systems. While our design may not be feasible for actual implementation with today's technology, it will serve as a roadmap for further development when the necessary advancements in optical components emerge.

Chapter 5

5. Conclusion

5.1. Summary of the Thesis

Recent advances and convergence of IP and optical networking, combined with the successful offerings of MPLS-based VPN services amount service providers, motivated the interests in Optical VPN. Chapter 1 gave an overview of optical networks and VPN technologies to establish a platform for further discussions.

Chapter 2 described the architecture of an all-optical VPN and looked at the current industry activities from the perspectives of equipment vendors, service providers, and standards bodies. We had also examined an all-optical VPN's general requirements, reconfigurability, switching methods, and survivability.

Chapter 3 jointly considered the effect of packet and optical connection services on WDM rings to enhance wavelength utilization. The idea is that we can provide ample bandwidth to packet based services by sharing the resources in the protection ring under normal network conditions. In case of a ring failure, the packet based channels can be compressed into fewer channels to yield protection bandwidth to circuit based services. Our simulation results have demonstrated that the proposed method to re-partition the wavelengths on the active and protection ring is able to make an improvement in the utilization for the protected wavelength connections due to reduced blocking. This observation is important because it is critical to show that redundancy can be maintained while we try to obtain resilience.

Chapter 4 presented a planar lightwave circuit based conceptual design for an All-Optical VPN Processing Engine. The result is a planar lightwave circuit based structure integrated with acousto-optic tuneable filter, Mach-Zehnder interferometers, and vertical cavity semiconductor optical amplifiers. Devices made with this design may be compatible with VLSI low-cost manufacturing in a small and reliable package to provide programmable functions targeted at OVPN applications on a single device.

We hope this conceptual design may lead to substantial new capability in next-generation communication systems. While our design may not be feasible for actual implementation with today's technology, it will serve as a roadmap for further development when the necessary advancements in optical components emerge.

5.2. Future Works

There are ample interests in all-optical VPN because its scope spans multiple layers of networking protocols and optical technologies. Future works on all-optical VPN could also be sorted into these areas.

We had jointly considered packet based and circuit based services to enhance wavelength utilization on a survivable WDM multi-ring network in Chapter 3. Another topic of interest for further wavelength utilization enhancement with potential application in OVPN is multi-granularity routing (by sub-wavelength, wavelength, waveband and fibre). There is already active work by IETF to adopt GMPLS to multi-granularity routing and it has been receiving increasing attentions.

Almost any type of advancement in optical technologies may find potential application related to OVPN, including wavelength routing and switching techniques, all kinds of optical signal processing methods, etc. More work is needed to investigate new elements to be included inside the OVPN PE to enhance its programmability and map additional functions on the device.

The fast provisioning and reconfiguration of OVPN service are crucial factors of successful deployment, which calls for further analysis of our OVPN PE's performance and search of methods to optimize our design. For example, if we ignore the active elements on the OVPN PE, we obtain an interconnection network of 2 x 2 switching cells. One may apply algebraic switching theory to seek an optimal solution for an interconnection network of planar waveguides to enhance the efficiency of the device. Prove of concept lab experiments are left to be done.

The demand for all-optical VPN service is accumulating as optical technologies dominates networks of the future. It is going to remain an innovative area of research in the foreseeable future.

Chapter 6

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