Network Capacity Improvement by Multicast in Elastic Optical Networks and Physical-Layer Network Coding in TDM-PON

WANG, Qike

A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree of

Master of Philosophy

in

Information Engineering

The Chinese University of Hong Kong

September 2012

Acknowledgement

First of all, I would like to express my deep and sincere gratitude to my supervisor Professor Lian-Kuan Chen for his excellent guidance, continuous encouragement and endless help. This thesis would never be completed without his professional knowledge, great patience and hard work. His critical thinking and careful attention to details are of great value in my life. I feel very fortunate to do research work under his supervision and benefit from his rich experience and wide knowledge.

Besides my advisor, I would like to express my sincere thanks to Prof. Chun-Kit Chan for his support on my research work and constructive comments in various topics. I would also like to thank Professor Soung-Chang Liew for his valuable discussions and careful review.

It is of my great honor and fortune to work with a group of intelligent, kind-hearted and nice colleagues in Lightwave Communication Lab, Department of Information Engineering, The Chinese University of Hong Kong. My warm thanks must be given to Dr. Ming Li, Dr. Jing Xu, Dr. Yang Qiu, Mr. Zhixin Liu, Mr. Kam-Hom Tse, Mr. Yeong-Tswen Tse, Mr. Wei Jia, Mr. Dong Shen, Ms. Pulan Li, Mr. Piu-Hung Yuen and Mr. Hong-Ton Lok.

I am especially thankful to my family for their continuous love, support and understanding. I owe them a lot more than a thank.

Abstract

Nowadays, with the information explosion, the capacity demand has been exponentially increasing in backbone networks and metro networks. Therefore, it is becoming a hot topic for both academic and industry to improve the network capacity. Elastic technologies are promising to scale up the network capacity due to just-enough bandwidth allocation for different data-rate traffic request, while physical-layer network coding (PNC) can increase the throughput without complex requirement on hardware. In this thesis, we first propose a novel scheme to improve the network capacity by implementing multicast in elastic optical networks. We further present the capacity improvement by integrating PNC in time-division multiplexing passive optical network (TDM-PON) for all-optical virtual private network (VPN) communications.

Analysis of multicast in elastic optical networks

Elastic optical networks can increase the spectrum utilization of backbone networks compared to the traditional wavelength-division multiplexing (WDM) networks due to flexible and just-enough bandwidth allocation. On the other hand, multicast over the optical layer is a bandwidth-efficient communication technique which supports point-to-multipoint applications. As many broadband services in the future can be from one source to several destinations, it is essential to enable optical multicast to save bandwidth as well as transceivers. To further improve the network throughput, we propose to implement multicast in spectrum elastic optical networks. Although many investigations on elastic optical networks have been carried out, to the best of our knowledge, the performance of multicast in elastic optical networks have not yet

been studied. We develop two efficient multicast heuristics to solve the multicast routing and spectrum allocation (MC-RSA) problem in elastic optical networks. By adopting the same routing and wavelength/spectrum allocation algorithms, the benefits of elastic optical networks resulting from flexible bandwidth allocation are studied for multicast compared to the traditional WDM networks. We also investigate the impact of spectral gap caused by non-uniform bandwidth allocation on the improvement of network throughput.

Physical-layer network coding (PNC) in TDM-PON

Network coding is a promising technique to improve the network throughput and robustness. Although network coding in TDM-PON has been recently investigated for exchanging information among optical network units (ONUs) in the same PON, the maximum capacity improvement of inter-ONU communications in these schemes is only 33%. In addition, large electrical buffer is required to store the VPN traffic at both optical line terminal (OLT) and ONUs. All-optical VPN in TDM-PON can optically reroute VPN traffic to the destined ONU without optical-electrical-optical conversion at OLT, which enables direct communications among ONUs. Here, to the best of our knowledge, for the first time, we experimentally demonstrate a novel PNC scheme integrated in TDM-PON for all-optical VPN communications to double the network throughput. A unique remote node that uses optical circulators to reduce the insertion loss of VPN communications is also proposed. By transmitting two inter-ONU traffic streams of opposite direction simultaneously using PNC (full-duplex), it can improve the network throughput by 100% compared to the traditional all-optical VPN schemes (half-duplex). Experiments show that error-free full-duplex VPN communications are achieved, and the power penalty is no more than 3 dB. Synchronization of ONUs is not required for the proposed scheme.

摘要

如今，隨著信息爆炸，骨幹網絡和城域網絡的容量需求已成倍增加。因此，如何提高網絡容量正成為學術界和工業界的熱門話題。可變帶寬光網絡技術通過為不同速率的數據傳輸分配剛剛足夠的帶寬來提高網絡容量，而物理層網絡編碼技術（PNC）在沒有復雜的硬件要求下可以增加網絡容量。在這篇論文中，我們首先提出將組播應用於可變帶寬光網絡來提高網絡容量。我們進一步提出將物理層網絡編碼技術應用於時分複用光接入網絡（TDM-PON），從而來提高全光虛擬專用通信（VPN）的網絡容量。

可變帶寬光網絡中組播的分析

可變帶寬光網絡相比傳統的波分複用光網絡（WDM）可以提高骨幹網絡的頻譜利用率，因為它可以靈活地分配剛剛足夠的帶寬。另一方面，光網絡層上的組播是一種高效的支持點對多點的通信技術。在未來的許多寬帶服務中，點對多點應用服務是必不可少的，通過光組播技術可以節省頻譜帶寬和接發器的數目。為了進一步提高網絡容量，我們建議在可變帶寬光網絡中進行組播。雖然關於可變帶寬光網絡的研究已經有很多了，但據我們所知，關於可變帶寬光網絡的組播尚未被研究。我們通過兩種有效算法來解決可變帶寬光網絡組播的路由和頻譜分配問題。採用相同的路由和波長/頻譜分配算法，我們研究了有靈活帶寬分配產生的好處，通過比較可變帶寬光網絡和傳統波分複用網絡的組播。我們也探討了由非均勻帶寬分配造成的頻譜間隙對提高網絡容量的影響。

時分複用光接入網中(TDM-PON)的物理層網絡編碼技術（PNC）

網絡編碼是一種很有前途的技術，可以提高網絡的容量和健全性。雖然最近有關於在時分複用光接入網中進行網絡編碼的研究，應用於同一個光接入網絡中的光

網絡單元（ONU）之間的通信，但在這些研究中的最大的網絡容量提高只有33％。此外，在光網路終端（OLT）和光網絡單元中還需要大量的緩衝來存儲VPN數據。在時分複用光接入網中，全光VPN網絡可以重新將VPN數據傳送到相應的ONU，實現ONU之間的直接通信，不需要在OLT進行光-電-光的轉換。在這裡，據我們所知，我們第一次用實驗驗證了一種新方案，將物理層網絡編碼技術應用於TDM-PON，使得全光VPN通信的網絡容量增加了一倍。我們也提出了在光接入網中的遠程節點處使用光環路器，以此減少VPN通信的插入損耗。當兩個ONU之間需要進行雙向通信，可以通過利用PNC來實現全雙工傳輸，相比傳統半雙工的全光VPN方案，網絡容量可以提高100％。實驗結果表明，可以實現無差錯全雙工VPN通信，相比半雙工通信功率補償不超過3分貝，而且這方案中ONU間的同步是不需要的。

Table of Contents

Chapter 1 Background

Nowadays, with the information explosion, the capacity demand has been dramatically increasing in both backbone networks and access networks. The global IP traffic is expected to grow at a compound annual growth rate (CAGR) of 29 percent from 2011 to 2016, whereas Internet video traffic will be 54 percent of all consumer Internet traffic in 2016 [1]. Therefore, the optimization of network resource is becoming a hot topic to improve the network capacity. Elastic technologies are proposed to scale up the capacity of backbone network, while low-cost and energy-efficient technology is promising to increase the throughput for access network. In this chapter, we introduce some important concepts, such as elastic optical networks, optical multicast, network coding in passive optical network (PON), all-optical virtual private network (VPN) in PON.

1.1 Elastic optical networks

Wavelength Division Multiplexing (WDM) technology has scaled up the capacity of backbone networks to hundreds of optical wavelengths with 100 Gb/s per wavelength in a single fiber, playing a major role in today's information explosion [2]. While WDM technology can provide large bandwidth to customers, it has some potential drawbacks. One of the drawbacks is the coarse and fixed bandwidth granularity (e.g., 50 GHz per wavelength) with fixed center wavelength in WDM networks, leading to low network efficiency, especially for the variable and time-dependent traffic demand. One entire wavelength must be assigned for a low data-rate traffic request even though it cannot make full use of the whole wavelength, leading to low spectrum utilization. On the other hand, super-wavelengths or super-channels larger than 100

GHz should be accommodated to satisfy extra high data-rate traffic demand that needs to occupy several optical carriers' bandwidth.

To improve the spectrum utilization of backbone network and satisfy different data-rate traffic demand with just enough bandwidth, spectrum elastic optical networks are proposed to enable flexible bandwidth allocation with a fine spectrum granularity [3]. In elastic optical networks, the necessary bandwidth is allocated in an integer multiples of 12.5 GHz, called frequency slot, thereby enhancing the spectrum utilization. For a low data-rate traffic request, a small integer multiples of frequency slots are allocated, while a large integer multiples of frequency slots are allocated for super-wavelengths. The authors in [4] experimentally demonstrated a multi-granularity optical network architecture, supporting flexible bandwidth allocation for different data-rate traffic demand varying from 12.5 Gb/s to 170.8 Gb/s.

To enable elastic technologies, optical orthogonal frequency division multiplexing (OFDM) plays a key role [5]. Bit rate-variable transponders based on optical OFDM technology can flexibly allocate the necessary bandwidth by simply adjusting the number of sub-carriers. Another important technology for elastic optical networks is the bandwidth-variable wavelength cross-connects (WXC), based on, for example, bandwidth-variable wavelength selective switch (BV-WSS) [6].

To better utilize the spectrum resource, elastic optical networks with flexible bandwidth allocation have attracted the interest of both the industry and academic. In [7], the benefits of elastic optical networks brought from flexible bandwidth allocation were investigated for unicast traffic, compared to the conventional wavelength-based WDM networks. The authors in [8] further studied the performance improvement by adopting traffic grooming in elastic optical networks, which benefits from the spectrum saving of filter guard band. In [9], a mini-grid case with a certain granularity which achieved almost the same performance with the gridless case is demonstrated by numerical simulations.

Distance-adaptive modulation formats

To future enhance the network efficiency in elastic optical networks, distance-adaptive modulation formats are proposed in [10]. With the advanced modulation technology, the simple return-to-zero (NRZ) on-off key (OOK) has been evolving to multi-level modulation format, such as polarization-multiplexed 16-ary quadrature-amplitude modulation (PM-16QAM) and PM-QPSK, using coherent detection technology and digital signal processing (DSP). Higher spectrum-efficient modulation formats require larger optical signal-to-noise ratio (OSNR), which limits the optical reach. Therefore, higher spectrum-efficient modulation formats such as PM-16QAM can be adopted for short distance, whereas more robust modulation formats such as PM-QPSK should be adopted for long distance. The modulation formats are chosen with just enough OSNR.

The authors in [11] experimentally demonstrated a novel super-wavelength transmitter architecture with adjustable bandwidth allocation and flexible modulation formats for dynamic distance transmission. It showed that the optical reach could achieve about 800 km, 1600 km and 6000 km for PM-16QAM, DP-8QAM and DP-QPSK respectively. The authors in [12] and [13] investigated the further improvement of network throughput in elastic optical networks by adopting distance-adaptive modulation formats through several numerical simulations.

Routing and spectrum allocation (RSA)

In elastic optical networks, the well-known routing and wavelength assignment (RWA) problem [14] for conventional WDM networks is extended to routing and spectrum allocation (RSA) problem. Different light-paths cannot share the spectrum resource on the same fiber links, which is referred to as the spectrum non-overlapping constraint. If no wavelength conversion is available, the light-path must occupy the same spectrum bandwidth on all the fiber links along the light-path, which is known as the spectrum-continuity constraint. It has been proved that the RWA problem is NP-complete [15]. Since the RWA problem is a special case of the RSA problem, the RSA problem is at least NP-complete. Similar to the RWA problem, the RSA problem can be partitioned into two sub-problems: the routing sub-problem and the spectrum allocation sub-problem. The new challenge in the spectrum allocation sub-problem is that an integer multiples of continuous frequency slots rather than a single wavelength should be allocated for each traffic request.

The RSA problem has been formulated as an integer linear program (ILP) which minimizes the overall required spectrum to improve the spectrum utilization given the traffic matrix [16, 17]. To solve the RSA problem efficiently, several heuristics have been proposed to serve each request sequentially. The *k* shortest paths for routing and first-fit for spectrum allocation are the most common for the RSA problem in both static and dynamic case [10, 13, 16, 18]. The authors in [16] also proposed several ordering policies in static case to minimize the spectrum usage, such as most-subcarriers-first ordering, longest-path-first ordering, and the combined optimal ordering.

1.2 Multicast in WDM networks

Multicast is a popular technique that enables the transmission of information from one source to multiple destinations. Multicast in WDM networks can efficiently improve the spectrum utilization as well as reduce the number of transceivers for some point-to-multipoint applications, such as video on demand (VoD), distance interactive learning, and video conference. It is forecasted by Cisco that Internet video traffic will be 54 percent of all consumer Internet traffic in 2016, up from 51 percent in 2011 [1]. The large amount of video traffic is of great potential to increase the multicast applications. To support multicasting traffic optically, the architecture of branching nodes should be multicast-capable. The capability of multicast can be easily realized with an optical splitter for duplicating optical signals and semiconductor optical amplifier (SOA) for on-off switching and amplifying.

Multicast routing and wavelength assignment (MC-RWA)

For efficiently implementing multicast in WDM networks, a light-tree instead of light-path should be established to transmit information from one source to multiple destinations [19]. The issue of finding a light-tree and assigning the wavelength on each branch along the light-tree for each multicast request is the well-known multicast routing and wavelength assignment (MC-RWA) problem. The key effort for MC-RWA problem is to minimize the overall blocking probability or maximize the total established multicast requests, given a set of multicast requests and a limited number of wavelengths.

To make the MC-RWA problem more tractable, the routing sub-problem and the wavelength assignment sub-problem can be solved separately. The solution of finding a minimum-cost light-tree is the Steiner Minimal Tree (SMT), which is NP-complete [20]. For the wavelength assignment sub-problem, two multicast requests cannot share the same wavelength on any common fiber link, known as the wavelength non-overlapping constraint. If no wavelength conversion is allowed, each multicast tree must be assigned the same wavelength, referred to as the wavelength-continuity constraint.

Most studies of multicast in wavelength-routed WDM networks focus on the MC-RWA problem. The authors in [21, 22] formulate the MC-RWA problem as an ILP for static traffic. Since ILP takes too much time for large networks or large number of traffic requests, more attention is paid to efficient heuristics. The authors in [23] developed an efficient approximation algorithm to minimize the overall cost, including the cost of using wavelengths on each fiber link and the cost of wavelength conversion. Jia *et al* in [24] proposed an optimization method by integrating routing and wavelength assignment to minimize the number of wavelengths, given a set of quality-of-service (QoS) multicast request. In [25], the authors proposed a simpler MAX-FIRST algorithm to minimize the user blocking probability, which serves the multicast request with larger number of destinations first. The authors in [26] studied the constrained multicast routing problem in WDM networks, where some switches were incapable of splitting optical signals.

1.3 Network coding in passive optical network (PON)

Network coding in optical networks

Network coding was originally proposed to improve the network throughput and robustness [27, 28]. Different from the traditional transport networks, where the intermediate nodes simply forward or drop the received bit stream, the nodes capable of network coding can send out the bit stream which is a predefined function of two or more received bit streams, such as the XOR function. This function, also known as the coding operation, plays a key role in improving the network throughput and robustness.

Several studies of network coding in optical networks have been carried out in order to take the advantage of network coding [29-35]. A. E. Kamal in [29, 30] proposed a 1+*N* protection scheme to protect multiple unicast connections against single link failures by performing network coding, which provides faster recovery time compared to conventional 1:N protection scheme. The authors in [31] implemented the network coding techniques in all-optical multicast networks to provide bandwidth-efficient, fast-recovery protection based on a simple photonic bitwise XOR device. In [32-35], the authors proposed to use network coding in passive optical network (PON) to achieve higher throughput and energy efficiency, as discussed in the following.

Network coding in PON

Time-division multiplexing (TDM) PON, for instance E-PON or G-PON, has been widely deployed for delivering access services due to its low cost and broadcast capability [36]. In TDM-PON, all optical network units (ONUs) share the upstream bandwidth by adopting the dynamic bandwidth allocation (DBA) protocol, while downstream traffic is broadcasted from optical line terminal (OLT) to all ONUs.

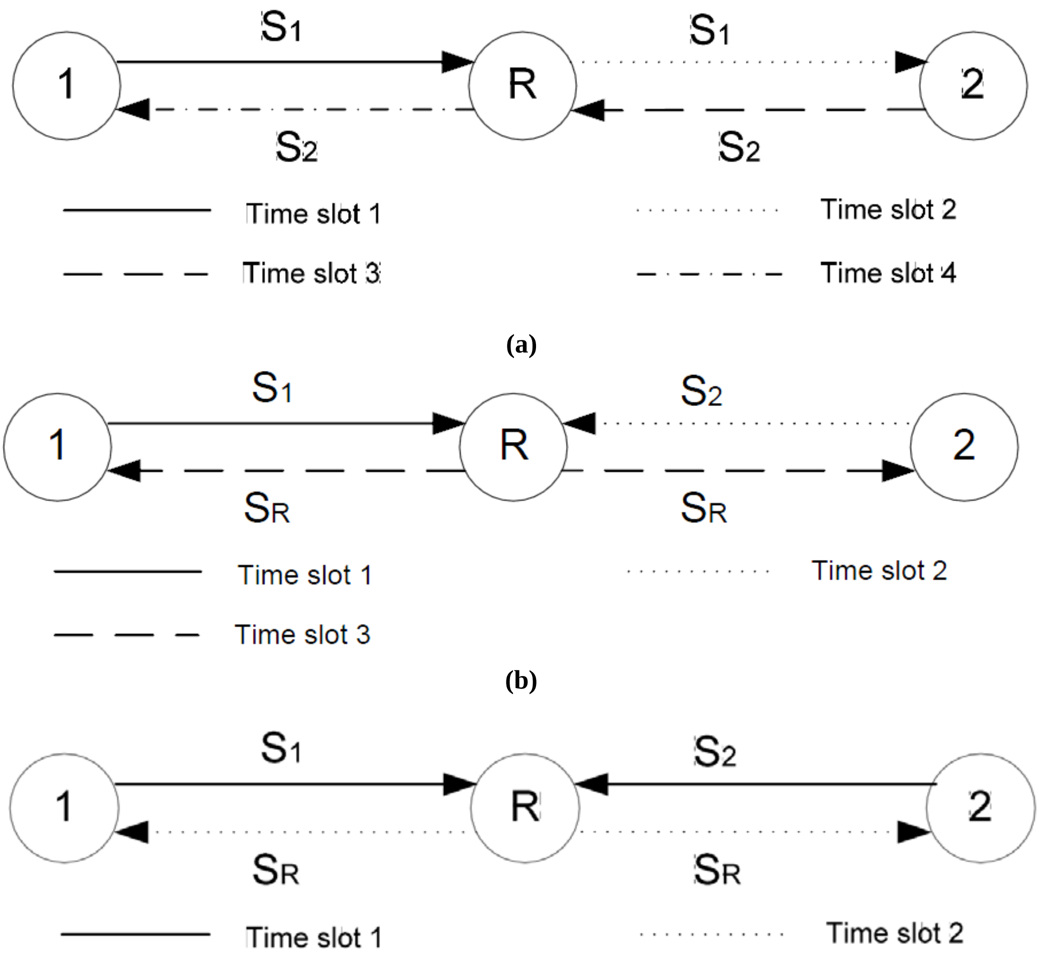
In recent years, the capacity demand in access network has been exponentially increasing due to the high bandwidth-required applications, such as high definition television (HDTV), video on demand (VoD), cloud computing. When upgrading to larger capacity in PON, it is essential to maintain low cost, easy operation, and energy efficiency. The authors in [32-35] proposed to implement network coding in TDM-PON, which can improve the network throughput by 33% for inter-ONU communication in the same PON, while the hardware keeps unchanged.

The implementation of network coding in previous schemes is as follows. Suppose ONU1 and ONU2 in the same TDM-PON need to communicate with each other. First, two inter-ONU traffic streams from ONU1 and ONU2 are transmitted to the OLT as upstream in different time slots by DBA and are then buffered at OLT electrically. The OLT then encodes the two traffic streams via predefined coding operation (e.g., XOR bits) and then broadcasts the encoded traffic stream to all ONUs as downstream. Only ONU1 and ONU2 can decode the right traffic stream by knowing its own traffic stream (i.e., the self-information). Compared to traditional inter-ONU communication without network coding in TDM-PON which requires two time slots for upstream and two time slots for downstream, the inter-ONU communication with network coding requires two time slots for upstream and one time slot for downstream, achieving 33% higher network throughput.

Physical-layer network coding (PNC)

Physical-layer network coding (PNC) was originally proposed in 2006 as a mean to increase throughput in wireless relay networks by implementing the network coding operation directly at the physical layer [37]. When two or more electromagnetic (EM) waves mix together, they add. This addition is a form of network coding realized by nature. As proposed in [37], with a two way relay channel (TWRC), PNC can improve the system throughput by 100%.

Fig 1.1 depicts a TWRC system of nodes 1 and 2 exchanging information via relay node R. Due to the half-duplex constraint in wireless communication system, a node cannot receive and transmit at the same time. With traditional non-network-coded scheme (TS) shown in Fig. 1.1 (a), total four time slots are required for nodes 1 and 2 to exchange information. By employing straight network coding (SNC, here we refer to the traditional network coding operation) in Fig. 1.1 (b), where relay node R sends a network coded-packet (e.g., $S_R = S_1 \oplus S_2$) in time slot 3, the number of total required time slots can be reduced to three, achieving a 33% throughput improvement. Nodes 1 and 2 can extract S_2 and S_1 from S_R respectively by knowing the local information. With PNC as depicted in Fig. 1.1 (c), the number of time slots can be further reduced to two, achieving a 100% throughput improvement. The operation principle of PNC is as follows. In time slot 1, relay node R receives the packets S_1 and S_2 simultaneously, while in time slot 2 the relay node R sends the combined packets S_R (S_R is the EM addition of S_1 and S_2) to nodes 1 and 2.



(c)

Fig 1.1. Two-way relay channel (TWRC) of (a) Traditional non-network-coded scheme (TS), (b) Straightforward network coding scheme (SNC), (c) Physical-layer network coding (PNC) [37].

Since PNC can improve the network throughput by 100%, much higher than the traditional network coding scheme, it is of great potential to implement PNC in TDM-PON. In Chapter 3, we will propose and experimentally demonstrate a novel scheme implementing PNC in TDM-PON, achieving 100% throughput improvement with error-free communications.

1.4 All-optical virtual private network (VPN) in PON

In traditional PON, only the upstream and downstream transmission between OLT and ONU are available, while two ONUs in the same PON cannot communicate with each other directly. The inter-ONU traffic must first be sent upstream to OLT and then broadcasted downstream to all ONUs, which consumes the bandwidth of both upstream and downstream, as well as increases the latency for inter-ONU communications.

To provide private and secure service, as well as to alleviate extra signal processing at OLT and reduce the latency, the all-optical virtual private network (VPN) was recently proposed to enable direct communications among ONUs in the same PON. In these previous schemes, the VPN traffic is optically routed at the remote node or at the OLT without optical-electrical-optical (O-E-O) conversion by using some special architectures or modulation formats. Most of the existing all-optical VPN schemes are built on TDM-PON, as TDM-PON is the most popular and widely deployed for delivering access service today [38].

To optically redirect the VPN traffic to the destined ONU, many approaches were proposed in previous works. C. J. Chae *et al* in [39] first implemented a Fiber Brag Grating (FBG) at the remote node to reflect a dedicated VPN's wavelength to all ONUs for all-optical VPN communications. Upstream and downstream traffic at other wavelength band is not interrupted due to the property of FBG. However, it has to experience high splitting loss caused by optical coupler twice, thereby reducing the number of customers that can be served. In [40, 41], the authors proposed to use dual distribution fibers to optically reroute the VPN traffic at the remote node and broadcast it to all ONUs. Although the dual distribution fibers can reduce the insertion loss, two distribution fibers can greatly increase the expense not only on the deployment of fibers but also on the maintaining. Another approach to compensate for the high splitting loss is to place a bidirectional amplifier at the OLT [42], which is only suitable for WDM-PON due to the cost issue. In addition, a cyclic $N \times N$ array waveguide grating (AWG) can optically reroute the VPN traffic among ONUs for WDM-PON [43].

To transmit the VPN traffic and upstream traffic simultaneously, various technologies are employed, such as dedicated transmitters for upstream and VPN traffic [39], sub-carrier modulation [41], orthogonal ASK/FSK modulation format [42]. Although these technologies can provide high flexibility for all-optical VPN communication, the additional cost and complexity may have great impact on cost-effective TDM-PON. To reduce the cost and complexity, VPN communication can share the same transmitter with upstream. The start time and length of time slot for each VPN transmission is also scheduled by DBA protocol at the OLT, which is the same as upstream transmission.

Although all-optical VPN has great advantages of enabling direct communications among ONUs, there are some potential drawbacks. In previous all-optical VPN schemes, only unidirectional inter-ONU communication (half-duplex) is allowed due to the star coupler architecture at the remote node. This limits the capacity of all-optical VPN communications. In Chapter 3, we will show that our proposed scheme can double the capacity for all-optical VPN communications in TDM-PON by employing PNC.

1.5 Contribution of this thesis

As discussed at the beginning of this chapter, the capacity demand has been continuously and exponentially increasing in backbone networks and metro networks. In this thesis, we first proposed a novel scheme to improve the network throughput by implementing multicast in elastic optical networks. We further present the capacity increase by integrating PNC in TDM-PON for all-optical VPN communications.

Analysis of multicast in elastic optical networks

As discussed above, elastic optical networks with flexible bandwidth allocation can increase the spectrum utilization of backbone network compared to the traditional WDM networks. On the other hand, multicast over the optical layer is a bandwidth-efficient communication technique which supports point-to-multipoint applications. It is essential to enable optical multicast, as many broadband services in the future can be from one source to several destinations.

To further improve the network throughput, we propose to implement multicast in spectrum elastic optical networks. Although many investigations on elastic optical networks have been carried out as mentioned in section 1.1, to the best of our knowledge, the performance of multicast in elastic optical networks have not yet been studied. We develop two efficient multicast heuristics to solve the routing and spectrum allocation (MC-RSA) problem for multicast in elastic optical networks. By adopting the same routing and wavelength/spectrum allocation algorithms, the benefits of elastic optical networks are investigated for multicast compared to the traditional WDM networks.

Physical-layer network coding (PNC) in TDM-PON

We have discussed about the existing schemes of network coding in TDM-PON in section 1.3. However, the maximum throughput improvement is only 33%, and it requires a large electrical buffer to store the VPN traffic at both OLT and ONU. Here, to the best of our knowledge, for the first time, we propose and experimentally demonstrate a novel PNC scheme integrated in TDM-PON for all-optical VPN communications. A unique remote node that uses optical circulators to reduce the insertion loss of VPN communications is also proposed in this part. By transmitting the VPN traffic between two ONUs simultaneously using PNC (full-duplex), it can improve the network throughput by 100% compared to the traditional all-optical VPN schemes (half-duplex). Experiments show that error-free full-duplex VPN communications are achieved, and the power penalty is no more than 3 dB. Synchronization of ONUs is not required for the proposed PNC scheme.

1.6 Organization of this thesis

The remaining part of this thesis is organized as follows:

Chapter 2 analyzes the multicast performance in elastic optical networks by numerical simulation with two efficient heuristics developed.

Chapter 3 experimentally demonstrates the proposed PNC scheme in TDM-PON for all-optical VPN applications. BER performance, power penalty and synchronization requirement induced by PNC will be investigated and discussed in this chapter.

Chapter 4 summarizes this thesis and discusses about the future potential research topics.

Chapter 2 Analysis of Multicast in Elastic Optical Networks

2.1 Introduction

As mentioned in Chapter 1, the capacity demand in backhaul networks has been exponentially increasing in the recent years. The global backhaul traffic is expected to increase by approximately a factor of 12 over the next decade [44]. Therefore, it has attracted both academy and industry to research on network capacity upgrade and optimization of network resource. Although the ITU-T wavelength-based WDM networks offer obvious advantages, the coarse granularity (e.g., 50 GHz per wavelength) leads to spectrum inefficiency when the traffic request is not sufficient to fill one entire wavelength. The recently proposed spectrum elastic optical networks, which introduce fine spectrum granularity, can improve spectrum utilization by flexible bandwidth allocation [3]. In elastic optical networks, the necessary spectral resource is allocated in an integer multiples of 12.5 GHz, called frequency slot. Therefore it is more efficient than traditional WDM optical networks based on 50-GHz grid. To flexibly allocate the just-enough bandwidth in elastic optical networks, two key technologies are i) bit rate-variable transponders based on optical orthogonal frequency division multiplexing (OFDM) [5] and ii) bandwidth-variable wavelength cross-connects (WXC) based on, for example, bandwidth-variable wavelength selective switch (BV-WSS) [6].

Multicast in WDM optical networks is a bandwidth-efficient technique that has enabled many popular point-to-multipoint applications, such as video conferencing, interactive distance learning. However, the low-rate multicast traffic demands cannot make full use of the whole wavelength capacity, leading to low bandwidth utilization. Therefore in order to increase the network efficiency, it is essential to implement multicast in spectrum elastic optical networks. The key issue to achieve high network efficiency in elastic optical networks is the multicast routing and spectrum allocation (MC-RSA) problem. To efficiently support optical multicast, a light-tree rather than a light-path should be constructed to solve the routing sub-problem [19]. If no wavelength conversion is allowed, the light-tree must transmit traffic on the same particular spectrum along the branches, which is the well-known spectral continuity constraint. Additionally, the channel setup for connections must follow spectral non-overlapping constraint, which means no spectrum overlapping for different channels on the same link.

The RSA problem for unicast in elastic optical networks with flexible bandwidth allocation has been studied recently [7, 10, 13, 16-18]. However, to the best of our knowledge, there are few investigations on the MC-RSA problem in elastic optical networks. In this chapter, we analyze the performance of multicast in spectrum elastic optical networks by developing two efficient heuristic algorithms. The multicast performance in elastic optical networks is compared to that in traditional wavelength-based WDM optical networks.

2.2 Network model and heuristics

2.2.1 Multicast-capable node architecture

To implement multicast in elastic optical networks, all nodes in the network should be capable of multicast in the optical layer with flexible bandwidth selection. Fig. 2.1 depicts the multicast-capable bandwidth-variable (BV) WXC node architecture, which consists of optical splitters, BV WSS and BV transponders. The optical splitters have the ability to duplicate the incoming optical signals with different bandwidth and broadcast the copy to all possible output ports. The band-variable (BV) WSS plays the key role in BV WXC node architecture for establishing all-optical connections with flexible bandwidth allocation. It can demultiplex/multiplex the optical signals with different wavelengths and perform the switching function. The BV transponders are able to transmit and receive bandwidth-variable optical signals with different centre wavelength using coherent technologies. For simplicity, the optical amplifying part for compensating for the splitting loss is not included in this figure.

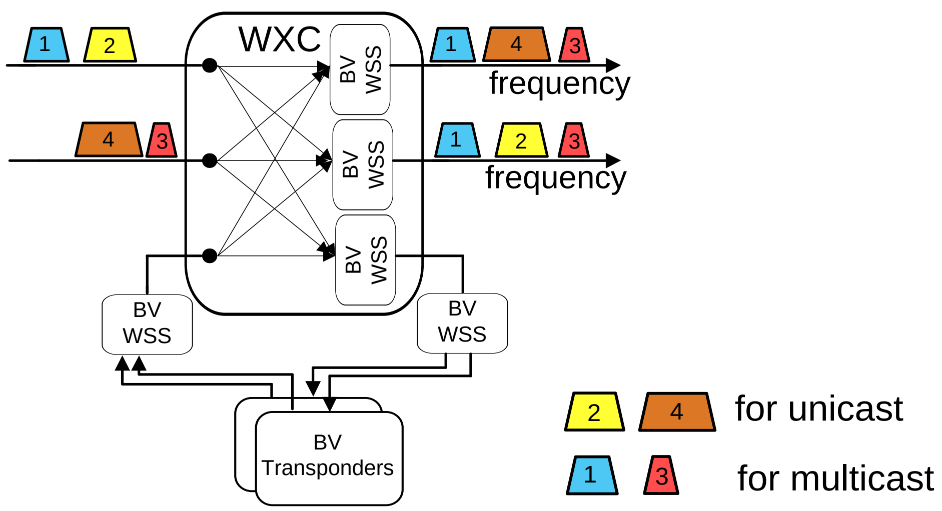


Fig 2.1. Multicast-capable bandwidth-variable (BV) wavelength cross-connects (WXC) node architecture. Channel 2 and channel 4 denote unicast traffic in frequency domain with different bandwidth; channel 1 and channel 3 denote multicast traffic in frequency domain with different bandwidth. BV WSS: bandwidth-variable wavelength selective switch.

2.2.2 Multicast group size (MGS) factor

Each multicast request has different number of destination nodes, namely multicast group size (MGS), varying from 1 to (N-1) where N is the total number of nodes in the network. The MGS factor is defined as follows:

$$\text{MGS factor} = \frac{\text{the } \textit{average} \text{ multicast group size}}{N-1}$$

where (N-1) denotes all the remaining nodes except the source node.

Without loss of generality, we assume that each node except the source node has the same probability to be the destination nodes independently (i.e., it follows the independent and identical distribution). It is clear to see that the MGS factor equals to this probability. For example, the 20% MGS factor means each node except the source node has the same probability of 20% to be the destination node independently. In the simulation, we assume that the whole multicast request will be blocked as long as any destination node cannot be served.

2.2.3 Network resource and assumption

We consider two network scenarios for comparison: 1) spectrum elastic optical networks with flexible bandwidth allocation; 2) traditional WDM optical networks with fixed bandwidth allocation. In elastic optical networks, due to the limitation of optical component resolution, we consider a fine spectrum grid based on 12.5-GHz frequency slot rather than the gridless case. The necessary bandwidth allocation for each request will be in multiples of continuous frequency slots. In comparison, the traditional wavelength-based WDM optical networks have fixed wavelength spacing (i.e., 50 GHz), which equals to four continuous frequency slots.

We assume the total available spectrum is 4000 GHz for both cases (320 frequency slots for elastic optical networks and 80 wavelengths for traditional WDM optical networks). When a multicast request arrives, an integer multiple of continuous frequency slots, adaptive to the data rate, is allocated for the flexible-allocation case (i.e., elastic optical networks). For the fixed-allocation case (i.e., traditional WDM optical networks), fixed wavelength-based bandwidth is assigned no matter how much bandwidth is required.

We assume each node in the network is equipped with multicast-capable WXC but no wavelength conversion is available. For simplicity, distance-adaptive modulation formats are not considered.

2.2.4 Multicast routing and spectrum allocation (MC-RSA) heuristics

To achieve high network throughput, it is essential to develop an efficient MC-RSA heuristic algorithm for multicast in elastic optical networks with flexible bandwidth allocation. For traditional wavelength-based WDM optical networks, there are many investigations on multicast routing and wavelength assignment (MC-RWA) [21-26]. Most of the algorithms separate the MC-RWA problem into the multicast light-tree routing sub-problem and wavelength assignment sub-problem. The algorithms for light-tree construction in route session are the variants of the shortest path tree (SPT) and the Steiner minimal tree (SMT). SPT is constructed to minimize the delay between the source node to each destination node, while SMT is constructed to minimize the total cost (e.g., the average spectrum utilization). SPT is constructed by

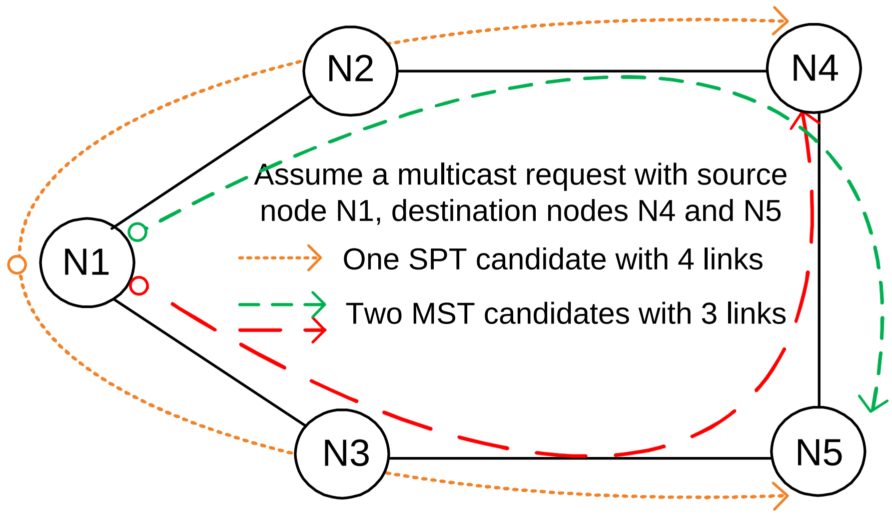


Fig. 2.2. An illustrative example for shortest path tree (SPT) and minimal spanning tree (MST)

connecting every source-destination node pair with the shortest path, while the SMT problem is NP-complete [20]. Hence, a well-known method to approximate SMT is to use minimal spanning tree (MST) [45]. One routing example for SPT and MST is shown in Fig. 2.2. For a multicast request with source node *N*1, destination nodes *N*4 and *N*5, there are one SPT candidate with four links and two MST candidates with three links.

In the numerical simulation, we use both SPT and MST for the route session in spectrum elastic optical networks to evaluate the multicast performance with flexible bandwidth allocation. To ensure fairness, the traditional wavelength-based WDM optical networks adopt the same routing algorithms. We also employ the first-fit (FF) algorithm for wavelength and spectrum allocation. Two efficient heuristic algorithms are developed for MC-RSA problem in spectrum elastic optical networks (shown as follows in Table. 2.1), namely SPT-FF and MST-FF.

Table 2.1. SPT-FF and MST-FF algorithms for MC-RSA problem in elastic optical networks

Step 1: Initialize the network topology and the overall free spectrum matrix. Pre-compute the shortest-path matrix for each node pair.
Step 2: Pick one multicast request in the order of arrival.
Step 3: Construct the SPT/MST route candidates for the multicast request using the shortest-path matrix. Among the SPT/MST route candidates, search for the first-fit (FF) necessary continuous frequency slots in ascending order of frequency slot index. If found, assign the FF continuous frequency slots along the respective SPT/MST route, and update the free spectrum matrix. If not, block the multicast request.
Step 4: Check all the current connections whose holding time expire, release the occupied frequency slots along the respective SPT/MST route, and update the free spectrum matrix.
Step 5: Repeat Step 2 to Step 4 for all the multicast requests.

2.3 Numerical results

In the simulation, we assume that the data rate for each multicast is uniformly distributed between 10 Gb/s and 40 Gb/s. The traditional wavelength-based WDM optical networks have the capacity equal to 40 Gb/s per wavelength with a fixed 50-GHz bandwidth. To be fair, four continuous frequency slots (12.5 GHz per frequency slot) in elastic optical networks can offer the same capacity of 40 Gb/s, so as to have the same bit/s/Hz. The elastic optical networks, however, provide more flexible bandwidth allocation, since we assume two or three continuous frequency slots can offer 20 Gb/s or 30 Gb/s, respectively.

The dynamic multicast request follows the Poisson distribution and the holding time for each connection is of negative exponential distribution. The source node and destination nodes for each multicast are selected randomly. A source node is first selected, and then the destination nodes are selected from all the remaining nodes independently with certain probability, which equals to the MGS factor as discussed above. Here we adopt 20%, 30% and 40% MGS factor for analysis. We use the NSF network (14 nodes, 21 bi-directional links) topology to evaluate the multicast performance in elastic optical networks. A total of 200000 arrival events are simulated with 5 times.

Figures 2.3 and 2.4 illustrate the blocking performance versus traffic load by employing SPT-FF algorithm and MST-FF algorithm, respectively. The results show that elastic optical networks with flexible bandwidth allocation offer lower blocking probability for multicast than the traditional WDM optical networks with fixed bandwidth allocation under different MGS. For SPT-FF with 30% MGS factor at blocking probability of 0.1, elastic optical networks can support 90 Erlangs more traffic load, increasing capacity by 25%. In addition, both algorithms show that flexible allocation with 40% MGS factor almost achieves the same blocking probability with fixed allocation with 30% MGS factor, which means that elastic optical networks can support 33% larger MGS. Smaller MGS has more improvement in blocking probability at the same traffic load. As expected, the MST-FF algorithm outperforms the SPT-FF algorithm on blocking probability because of more efficient light-tree employed.

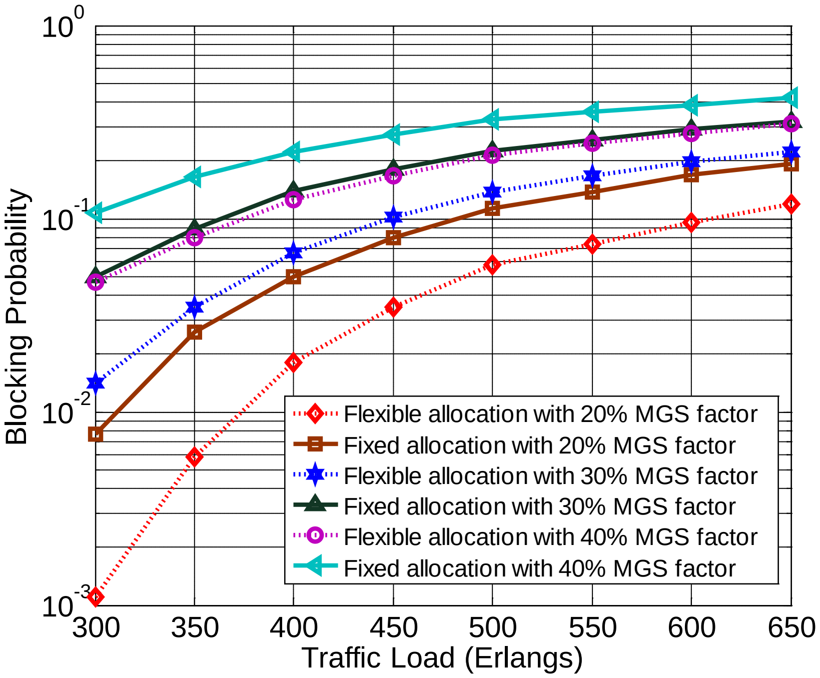


Fig. 2.3. Blocking probability versus traffic load employing SPT-FF algorithm

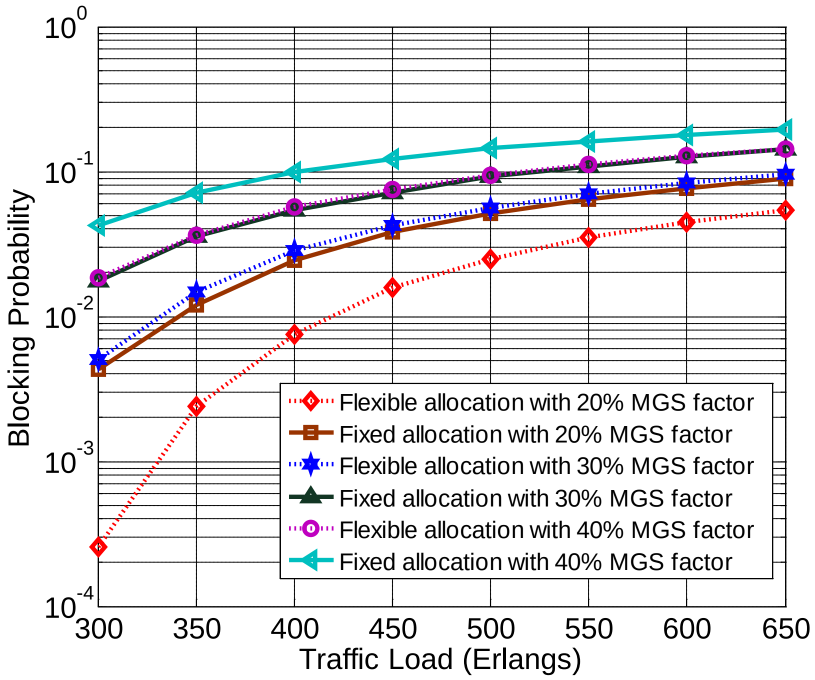


Fig. 2.4. Blocking probability versus traffic load employing MST-FF algorithm

Although the flexible bandwidth allocation in elastic optical networks can improve the network improvement shown as above, the spectral gap caused by non-uniform frequency slot allocation make fragmented spectrum difficult to use. Therefore, the non-uniform spectrum usage may limit the improvement of network capacity. We would like to investigate the effect of the spectral gap on the improvement of network throughput. Since the fixed-alternative routing and first-fit algorithm is adopted in the simulation, more unused spectrum in elastic optical networks leads to lower improvement of network throughput at certain blocking probability. We use the normalized unused spectrum to evaluate the performance of network throughput at certain blocking probability.

Figures 2.5 and 2.6 compare the normalized unused spectrum of elastic optical networks and traditional WDM optical networks at blocking probability of 10%. The results show the normalized unused spectrum for elastic optical networks is about 8% higher, indicating that the spectral gap limits the improvement of network throughput. It is also shown that for a fixed blocking probability, the normalized unused spectrum is nearly independent of MGS.

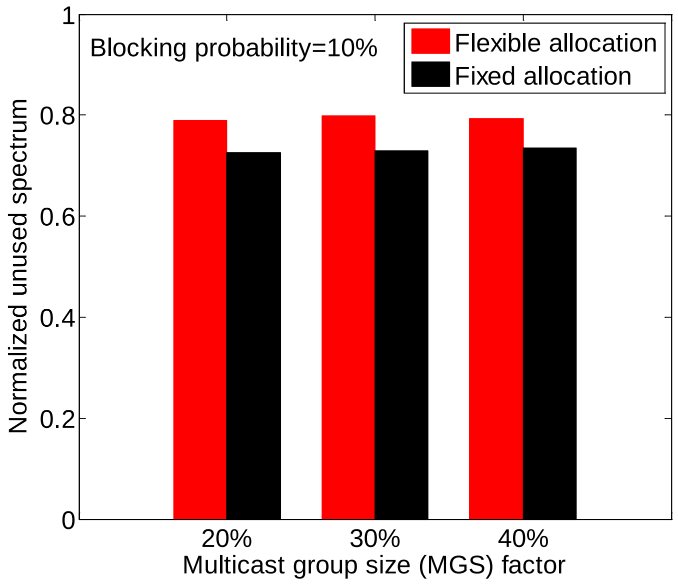


Fig. 2.5. Normalized unused spectrum comparison employing SPT-FF algorithm

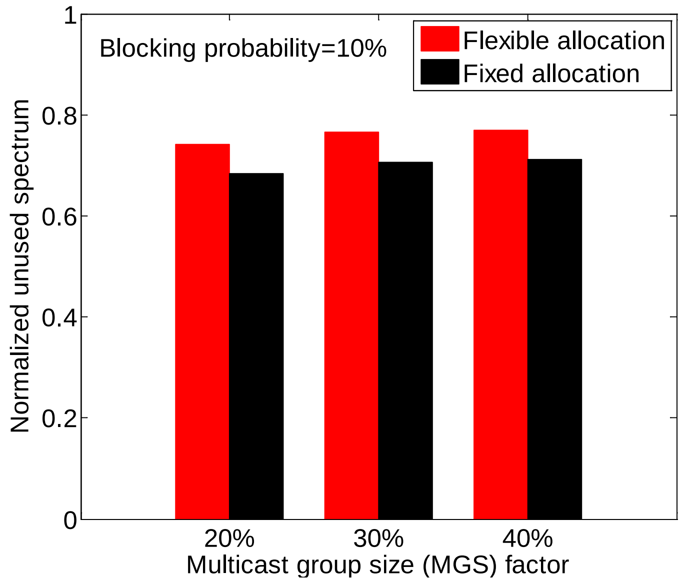


Fig. 2.6. Normalized unused spectrum comparison employing MST-FF algorithm

2.4 Summary

We investigate the multicast performance in spectrum elastic optical networks by developing two heuristic algorithms. Simulation results show that the flexible spectrum allocation in elastic optical networks provides lower blocking probability for multicast compared to the traditional wavelength-based WDM optical networks. However, the spectral gap in elastic optical networks, caused by non-uniform frequency slot allocation, has slightly limited the improvement of network throughput.

Chapter 3 Physical-Layer Network Coding (PNC) in TDM-PON

3.1 Introduction

Time-division multiplexing (TDM) passive optical network (PON), e.g. E-PON or G-PON, has been widely deployed for delivering access services due to its low cost and broadcast capability [36]. In a TDM-PON system, downstream is broadcasted from optical line terminal (OLT) to all optical network units (ONUs) and upstream from ONU to OLT is shared among all ONUs by dynamic bandwidth allocation (DBA) protocol. Conventionally, two ONUs in the same PON cannot communicate with each other directly. The inter-ONU traffic must first be sent upstream to OLT and then broadcast downstream to all ONUs, wasting bandwidth in both directions.

To provide private and secure service, as well as to alleviate extra signal processing at the OLT, all-optical virtual private network (VPN) was recently proposed to enable direct communication among ONUs in the same PON. For optically rerouting the inter-ONU traffic to the destined ONU without occupying upstream and downstream bandwidth resources, various all-optical VPN schemes were proposed [38-43]. The authors in [39] implemented a Fiber Brag Grating (FBG) at the remote node to optically reflect the inter-ONU traffic to all ONUs, while the authors in [40, 41] proposed to use dual distribution fibers to reduce the insertion loss caused by the power splitter at the remote node.

However, only unidirectional inter-ONU communication (half-duplex) is allowed in these schemes due to the star coupler's architecture at the remote node. This limits the capacity of all-optical VPN communications.

Network coding was originally proposed to increase network throughput [27, 28] and has recently been investigated for application in optical networks, including PONs [29-35]. In next-generation PONs, the inter-ONU traffic will increase because of emerging applications and services such as the smart grid [46]. The authors in [32, 33] proposed to integrate network coding with TDM-PON to improve the throughput of bidirectional inter-ONU communication. The improvement of throughput by employing network coding was investigated by numerical simulation in these papers. In [34], the authors implemented network coding for next-generation PONs and fiber-wireless access network system.

However, in all these schemes, the encoding and decoding operation are implemented logically after optical-to-electrical conversion. Two inter-ONU traffic streams of opposite directions are transmitted to the OLT as upstream in different time slots by DBA protocol and are then buffered at OLT electrically. The OLT then encodes the two traffic streams via predefined coding operation (e.g., XOR bits) and then broadcasts the encoded traffic stream to all ONUs as downstream. The respective ONU can decode the right traffic stream by buffering a copy of its own traffic stream (i.e., the self-information). However, it requires large electrical buffer at OLT to store the two inter-ONU traffic streams and occupies additional downstream bandwidth. The coding operation at OLT also increases the workload and consumes additional power. The maximum capacity improvement for inter-ONU communication in these schemes is only 33%.

In this paper, we propose and demonstrate a novel scheme that implements physical-layer network coding (PNC) in TDM-PON for all-optical VPN applications for the first time. The scheme can increase the network throughput of inter-ONU communication by 100%. In addition, a unique remote node that uses optical circulators to reduce the insertion loss is proposed for all-optical VPN communication.

PNC was originally proposed in 2006 as a means to increase throughput in wireless relay networks by implementing the network coding operation directly at the physical layer [37]. When two or more electromagnetic (EM) waves mix together, they add. This addition is a form of network coding realized by nature. A comparison of PNC, straightforward network coding (SNC) and non-network coding has been discussed in Chapter 1. The throughput improvement by employing PNC can reach 100%, while the throughput improvement by employing SNC is only 33%. Although PNC has been widely studied in wireless networks, its application in optical networks has hardly been explored. The authors in [47] experimentally demonstrated a PNC scheme in optical layer by combining two polarizations for optical protection. In this chapter, we experimentally demonstrate that PNC can be applied to all-optical VPN applications in TDM-PON. In the proposed scheme, PNC can increase the network throughput of VPN communication by 100%, as well as provides more secure service.

3.2 A novel PNC in TDM-PON scheme for all-optical VPN applications

3.2.1 System architecture

Fig. 3.1 depicts the proposed PNC in TDM-PON architecture for all-optical VPN applications. First of all, a unique remote node (RN) architecture for all-optical VPN communication is proposed, in which the VPN traffic and upstream traffic only experience single-pass splitting loss. At the remote node, each port 1 of the (N+1) three-port optical circulators is connected to one output port of a (N+1)×(N+1) optical coupler while each port 3 is connected to one input port of that coupler. One circulator is connected to the OLT while the others are connected to N ONUs. The (N+1) three-port optical circulators are used such that the optical signal only experiences the high splitting loss caused by optical coupler once. For a 1×32 coupler, it corresponds to ~13-dB reduction in the insertion loss, assuming that the splitting loss is around 15-dB and the insertion loss for the additional circulator is around 1 dB per pass. The conventional all-optical VPN schemes in TDM-PON may use a

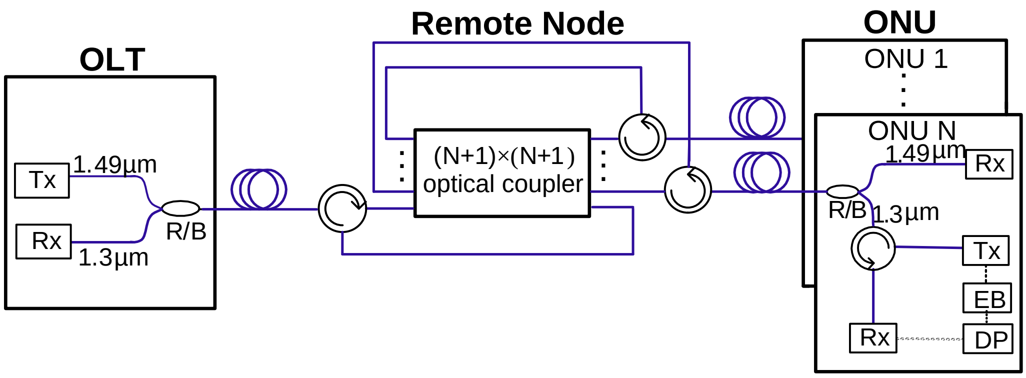


Fig. 3.1. Proposed PNC in TDM-PON architecture for all-optical VPN applications. R/B: red/blue coupler. Tx: transmitter. Rx: receiver. EB: electrical buffer. DP: decoding process. Downstream wavelength: 1.49um. Upstream wavelength: 1.3um.

narrow-band FBG, in which the optical signal has to pass through the splitting loss caused by optical coupler twice [39], or use dual distribution fibers [40, 41]. Like the traditional TDM-PON, in the proposed scheme upstream and downstream can transmit simultaneously with the use of red/blue coupler. The VPN traffic is optically rerouted at the remote node and then broadcast to all ONUs, including the destined ONU and own ONU.

To reduce the cost and power consumption, in the proposed scheme the upstream and VPN communication share the same transmitter at each ONU, whereas [39] has separate transmitters for upstream and VPN communication. To transmit the upstream data and VPN data simultaneously at each ONU, [41] uses subcarrier multiplexer and [42] adopts orthogonal ASK/FSK modulation format, thereby increasing the ONU complexity. Collisions between the upstream and inter-ONU VPN communications are avoided by DBA protocol at the OLT.

3.2.2 Implementation of PNC

If two ONUs need to communicate with each other over the all-optical VPN, the OLT allocates time slots for them and no upstream is transmitted during that time. For the aforementioned VPN schemes without implementing PNC, only one ONU is allowed to send the inter-ONU traffic in one time slot (half-duplex mode) since all ONUs will receive the inter-ONU traffic. It requires totally two time slots for two ONUs to exchange information, i.e., one ONU sends its VPN traffic in the first time slot and then the other ONU sends the VPN traffic in the second time slot. By employing PNC in the proposed scheme, two ONUs are allowed to transmit optical inter-ONU signals at the same time (full-duplex mode), thereby requiring only one time slot to complete the inter-ONU communication. As such, it can increase the throughput of inter-ONU communications by 100%, compared to the conventional half-duplex scheme without employing PNC.

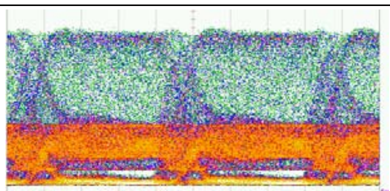
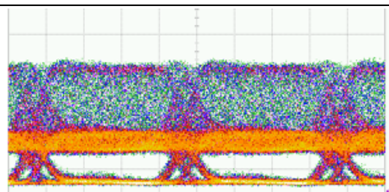
The implementation of PNC in TDM-PON for all-optical VPN applications is as follows. For the encoding process (EP), two optical VPN signals from two ONUs are combined together at the remote node and then are optically looped back to all ONUs. For the decoding process (DP), the respective ONU receives the combined optical signal (i.e., its own optical signal and the other ONU's signal), and then converts the optical signal into electrical signal. By subtracting the original copy of the electrical signal buffered previously (i.e., the self-information) from the detected electrical signal, the respective ONU can obtain the other ONU's signal. Although the other ONUs can also receive the combined optical signals, they cannot operate the decoding process without knowing the self-information. The EP and DP in this scheme do not require the synchronization between two ONUs, thereby greatly enhancing the feasibility of this scheme.

3.2.3 Management of wavelength collision

For simplicity, this chapter experimentally demonstrates PNC employing the natural property of optical power addition. Therefore, two optical signals from the respective ONUs for VPN communication should have different central wavelengths to avoid the interference noise caused by wavelength collision. To allow for all-optical full-duplex VPN communication with PNC between any two colorless ONUs, each ONU should have two different central wavelengths, short and long wavelengths, with coarse tunable capability. Here, there is no requirement on the exact values of the wavelengths among different ONUs.

We investigate the requirement of wavelength difference between two ONUs for all-optical VPN communications to eliminate the interference noise. Fig. 3.2 shows the eye diagrams of two combined optical signals versus wavelength difference detected by a 10-Gb/s p-i-n receiver. It is shown that a wavelength separation of 0.3 nm is sufficient to avoid the interference noise and there is no requirement on the exact values for the two wavelengths.

Low-cost coarse wavelength tuning at ONU can be easily realized by adjusting temperature or injection current. The wavelength-tuning mechanism can be controlled by the OLT using an upper layer protocol. When establishing full-duplex VPN communication between two ONUs, the OLT sends downstream data, including temperature or injection current parameters, to respective ONUs to select the short or long wavelengths. Here we assume that the laser can be coarsely tuned to the short or long wavelength band.

wavelength differences	$\Delta\lambda$= 0 nm	$\Delta\lambda$= 0.1 nm
		

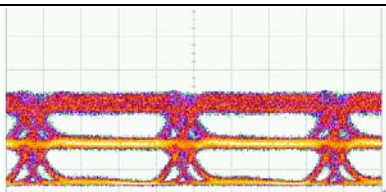
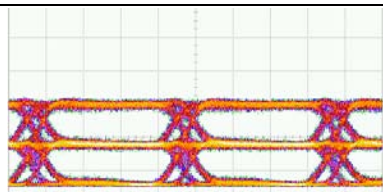
wavelength differences	$\Delta\lambda$= 0.2 nm	$\Delta\lambda$= 0.3 nm
		

Fig. 3.1. Eye diagrams versus wavelength differences

Although it is possible to filter out the signal from the other ONU by a tunable wavelength filter, this introduces higher cost and requires complex operation of precise wavelength matching. For our proposed PNC system, precise wavelength matching is not needed.

3.3 Experiments and results

Fig. 3.3 shows the experimental setup for the full-duplex all-optical VPN inter-ONU communications that employ PNC in TDM-PON. Since we only aimed to demonstrate the inter-ONU VPN communication that employs PNC, the OLT was not included in the experimental verification.

At ONU2, a continuous wave (CW) light at 1548.73 nm was intensity-modulated by a 2.5-Gb/s 27-1 pseudorandom binary sequence (PRBS) not-return-zero (NRZ) data before electrical delay line (EDL), which was used to adjust time misalignment between two ONUs for investigating the requirement for synchronization. At ONU1, a CW light at 1552.00 nm was intensity-modulated by a 2.5-Gb/s 27-1 PRBS NRZ data. The length of the distribution fiber for ONU2 was 2 km, while the length of the distribution fiber for ONU1 was 10 km. The 10-km distribution fiber was adopted to study the effect of long distribution fiber in TDM-PON and to investigate the influence of Rayleigh back scattering (RBS) [48]. Two optical signals were combined at the remote node, which consisted of one 2×2 optical coupler and two 3-port optical circulators. Each port 1 of the two optical circulators was connected to one side of the

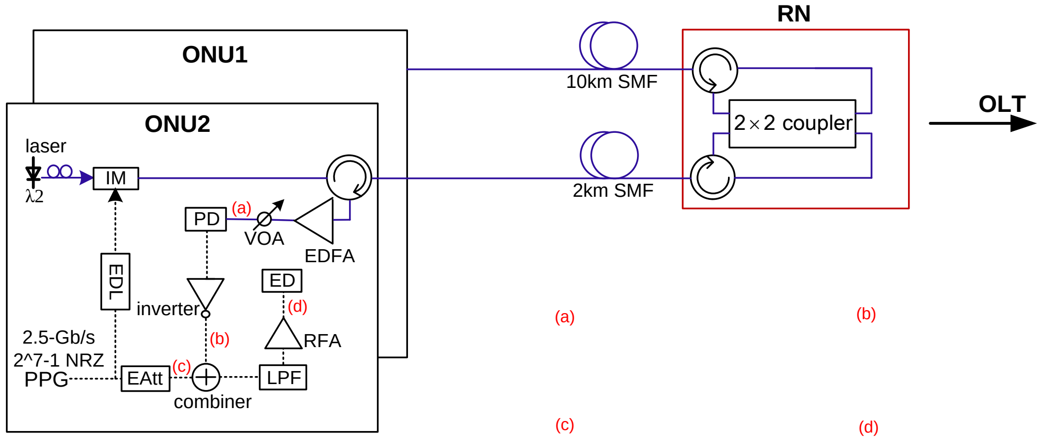


Fig. 3.3. Experimental setup. Insets show (a) the received two optical signals; (b) the received two electrical signals after photodiode and electrical inverter; (c) the own copy of electrical signal; (d) the decoded electrical signal. IM: intensity modulator; EDL: electrical delay line; EDFA: Erbium doped fiber amplifier; VOA: variable optical attenuator; PD: photodiode; LPF: low pass filter; EAtt: electrical attenuator; RFA: radio frequency amplifier; ED: error detector; RN: remote node.

2×2 optical coupler, was connected to the other side of that coupler. Port 2s of the two optical circulators were connected to ONU1 and ONU2. Hence, the remote node performed as a star coupler, and the combined optical signal was looped back to both ONU1 and ONU2. The erbium doped fiber amplifier (EDFA) and variable optical attenuator (VOA) in this scheme were just for measuring the receiver sensitivity. After passing through EDFA and VOA, the combined optical signal was converted into electrical signal by a 10-Gb/s p-i-n receiver, which was integrated with an electrical inverter. The converted electrical signal was combined with the original copy of own electrical signal buffered using an electrical combiner for the decoding process. The voltage of the buffered electrical signal was adjusted through an electrical attenuator (EAtt) to achieve the self-signal cancellation in the received electrical signal. The decoded electrical signal passed through a 2.34-GHz low pass filter (LPF) and a radio frequency amplifier (RFA), and was then fed into the error detector (ED) for bit-error-rate (BER) test. To achieve burst mode operation with PNC, some alternation on the conventional burst-mode receivers [49] is required. For the modified burst-mode receivers, the cancellation of its own copy is performed after the photodetector, using a cancellation circuit followed by the conventional burst-model receiver circuit.

The inset (a) in Fig. 3.3 shows the eye diagram of the combined two optical signals with time misalignment, while inset (b) shows the eye diagram before the electrical combiner, demonstrating the scrambling of the original data when the two ONUs are transmitting concurrently. The inset (c) is the eye diagram of original electrical signal, and the inset (d) is the decoded signal after passing through LPF and RFA.

We have measured the bit error rate (BER) performance of all-optical VPN inter-ONU communications with and without PNC. Fig. 3.4 shows that ONU2 with 2-km distribution fiber achieves BER=10^{-9} at about -18 dBm with PNC for VPN communications. The power penalty caused by employing PNC is nearly 3 dB compared to the half-duplex scheme, due to the non-ideal waveform cancellation in the decoding process. The rising and falling edges of electrical signal have changed after electrical-optical-electrical conversion. As the received power decreases, the power penalty becomes smaller because the noise caused by non-ideal waveform cancellation has less influence on the BER performance. However, ONU1 with 10-km distribution fiber achieves BER=10^{-9} at about -16 dBm with PNC, almost 2 dB worse than that for ONU2 with 2-km distribution fiber. The 10-km distribution fiber suffers from more severe Rayleigh backscattering, thereby degrading the BER performance. Note that most typical distribution fiber has a length less than 5 km in TDM-PON and will experience less degradation from Rayleigh scattering. Fig. 3.5 shows the required power at BER=10^{-9} versus different timing misalignment of two ONUs' signals. The variation of required power is smaller than

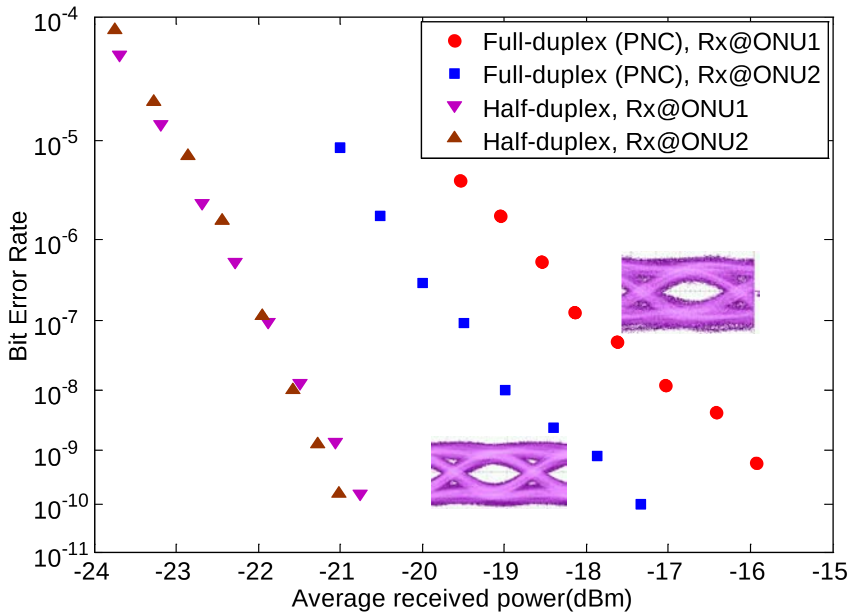


Fig. 3.4. BER performance comparison of full-duplex (PNC) and half-duplex

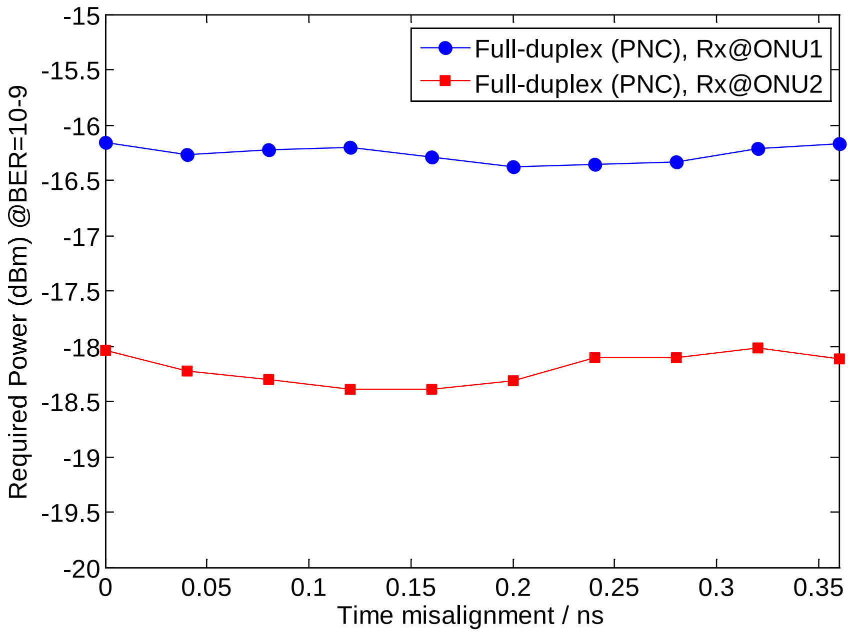


Fig. 3.5. Required power @BER=10^{-9} versus different time misalignment of two optical signals

0.4 dB. Therefore the synchronization of two ONUs is not required for the proposed scheme, which greatly enhances the feasibility.

3.4 Summary

For the first time, we experimentally demonstrate an all-optical PNC scheme with error-free full-duplex communication in TDM-PON for VPN applications at bit rate of 2.5 Gb/s. By employing PNC, the capacity for inter-ONU communication increases by 100% while the power penalty is no more than 3 dB for 2-km-length distribution fiber at BER=10^{-9}. A unique RN that uses optical circulators to reduce the insertion loss of inter-ONU traffic is proposed for all-optical VPN communications. We also show that the synchronization of two ONUs is not required for the scheme. The proposed scheme can be realized with low-cost simple devices.

Chapter 4 Conclusion and Future Works

4.1 Conclusion of this thesis

To meet the increasing capacity demand, this thesis proposed two novel schemes to improve the network throughput. In Chapter 2, we first propose to implement optical multicast in elastic optical networks to increase the network efficiency of backbone networks. We further present the capacity increase by integrating PNC in TDM-PON for all-optical VPN communications in Chapter 3.

As elastic optical networks can increase the spectrum utilization with flexible bandwidth allocation, we investigate the performance of optical multicast in elastic optical networks with two efficient heuristics developed. Numerical simulations show that elastic optical networks can provide lower blocking probabilities than traditional WDM networks for optical multicast under different MGS factors. We also study the impact of spectral gap caused by non-uniform bandwidth allocation on the improvement of network throughput. It shows that spectral gap slightly limits the improvement.

In addition, we propose and experimentally demonstrate a novel PNC scheme in TDM-PON for all-optical VPN communications. It can improve the network throughput by 100% compared to the traditional all-optical VPN scheme without the requirement of complex hardware. Error-free full-duplex all-optical 2.5-Gb/s VPN transmission is achieved with power penalty no more than 3 dB. It is also experimentally shown that the synchronization of two ONUs for VPN communications is not required and a wavelength separation of 0.3 nm is sufficient to avoid interference noise caused by wavelength collisions. A unique remote node that uses optical circulators to reduce the insertion loss is also proposed to achieve all-optical VPN communications. The proposed scheme can be realized with low-cost simple devices.

4.2 Future works

In Chapter 2, simulation results show that although the flexible bandwidth allocation in elastic optical networks can help improve the network throughput, the spectral gap caused by non-uniform bandwidth allocation slightly limits the improvement. The reason is that the first-fit (FF) algorithm is not efficient to reduce the spectral gap. Future work will focus on developing more efficient spectrum allocation algorithm to further improve the network throughput.

In Chapter 3, we have experimentally demonstrated full-duplex 2.5-Gb/s all-optical VPN communications by employing PNC in TDM-PON. According to the BER test in Chapter 3, the PNC scheme has potential for error-free full-duplex 10-Gb/s transmission. If PNC could double the throughput for 10-Gb/s transmission with acceptable power penalty, it would be applicable to other optical systems, such as hybrid WDM/TDM PON, bidirectional communications among data centers.

To achieve 100% throughput improvement, the two inter-ONU traffic should have the same data length and be exactly aligned. It is important to maximize the throughput improvement. We will schedule the inter-ONU traffic to improve the efficiency in the further research. In addition, we assume that the received own signal is synchronized with its own copy of information stored in the electrical buffer for the decoding process. Further research will include the requirement for synchronization as well as the corresponding penalty. The effect of uneven powers received at ONU due to the unequal distribution fiber lengths should also be considered.

Experimental results also show that the power penalty by employing PNC for 2-km-length distribution fiber is around 3 dB at BER=10^{-9}, caused by non-ideal waveform cancellation. Theoretically, the power penalty can be as small as 0 dB with the ideal waveform cancellation. It is possible to reduce the power penalty with some signal processing methods. Additionally, the Rayleigh backing scattering (RBS) noise with 10-km-length distribution fiber increases the required power at BER=10^{-9} by around 2 dB. Prior approaches for reducing RBS noise is not suitable for this scheme, since the own optical signal's spectrum is the same as the spectrum of RBS noise. New methods to reduce this kind of RBS noise are essential for optical systems with long fibers, should PNC be employed to increase the network throughput.

Bibliography

[1] Cisco Systems, *Inc.*, “Cisco visual networking index – forecast and methodology, 2011-2016,” white paper, May 2012.

[2] Peter J. Winzer, “Beyond 100G Ethernet,” *IEEE Commun. Mag.*, vol. 48, no. 7, pp. 26-30, July 2010.

[3] M. Jinno, H. Takara, B. Kozicki, Y.Tsukishima, Y. Sone and S. Matsuoka, “Spectrum-Efficient and Scalable Elastic Optical Path Network: architecture, benefits, and enabling technologies,” *IEEE Commun. Mag.*, vol. 47, pp. 66-73, Nov. 2009.

[4] N. Amaya, I. Muhammad, G. S. Zervas, R. Nejabati, D. Simeodinou, Y. R. Zhou and A. Lord, “Experimental Demonstration of a Gridless Multi-granular Optical Network Supporting Flexible Spectrum Switching,” *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper OMW3, 2011.

[5] A. J. Lowery *et al.*, “Performance of Optical OFDM in Ultralong-Haul WDM Lightwave Systems,” *IEEE/OSA J. Lightw. Technol.*, vol. 25, no. 1, pp. 131-138, Jan. 2007.

[6] K. Yonenaga, A. Takada, Y. Aoki and S. Kinoshita, “Demonstration of 100-Tbit/s Scale Multiple Granularity OXC Architecture,” *IEEE/OSA European Conference on Optical Communication (ECOC)*, Paper 2.5.5, 2009.

[7] K. Christodoulopoulos, I. Tomkos and E. Varvarigos, “Spectrally/Bitrate Flexible Optical Network Planning,” *IEEE/OSA European Conference on Optical Communication (ECOC)*, Paper We.8.D.3, 2010.

[8] Y. Zhang, X. Zheng, Q. Li, N. Hua, Y. Li and H. Zhang, “Traffic Grooming in Spectrum-Elastic Optical Path Networks,” *IEEE/OSA Optical Fiber Communication*

Conference / National Fiber Optic Engineers Conference (OFC/NFOEC), paper OTuI1, 2011.

[9] G. (Steven) Shen and Q. Yang, “From Coarse Grid to Mini-Grid to Gridless: How Much can Gridless Help Contentionless?” *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper OTuI3, 2011.

[10] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka and A.Hirano, “Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network,” *IEEE Commun. Mag.*, vol. 48, no. 8, pp. 138-145, Aug. 2010.

[11] Y.-K. Huang, E. Ip, P. N. Ji, Y. Shao, T. Wang, Y. Aono, Y. Yano and T. Tajima, “Terabit/s Optical Superchannel with Flexible Modulation Format for Dynamic Distance/Route Transmission,” *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper OM3H.4, 2012.

[12] T. Takagi, H. Hasegawa, K. Sato, T. Tanaka, B, Kozicki, Y. Sone and M. Jinno, “Algorithm for Maximizing Spectrum Efficiency in Elastic Optical Path Networks that Adapt Distance Adaptive Modulation,” *IEEE/OSA European Conference on Optical Communication (ECOC)*, Paper We.8.D.5, 2010.

[13] T. Takagi, H. Hasegawa, K. Sato, Y. Sone, B. Kozicki, A. Hirano and M. Jinno, “Dynamic Routing and Frequency Slot Assignment for Elastic Optical Path Networks that Adopt Distance Adaptive Modulation,” *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper OTuI7, 2011.

[14] H. Zang, J. P. Jue and B. Mukherjee, “A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks,” *SPIE Opt. Netw. Mag.*, vol. 1, no. 1, pp. 47–60, Jan. 2000.

[15] I. Chlamtac, A. Ganz and G. Karmi, “Lightpath communications: an approach to

high bandwidth optical WAN's," *IEEE Trans. Commun.*, vol. 40, no. 7, pp.1171-1182, July 1992.

[16] K. Christodoulopoulos, I. Tomkos and E. A. Varvarigos, "Routing and Spectrum Allocation in OFDM-Based Optical Networks with Elastic Bandwidth Allocation," *IEEE Global Telecommunications Conference (GLOBECOM 2010),* vol., no., pp.1-6, Dec. 2010

[17] Y. Wang, X. Cao and Q. Hu, "Routing and Spectrum Allocation in Spectrum-sliced Elastic Optical Path Networks," *Proc. International Conference on Communications (ICC), IEEE,* June 2011.

[18] X. Wan, L. Wang, N. Hua, H. Zhang and X. Zheng, "Dynamic Routing and Spectrum Assignment in Flexible Optical Path Networks," *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC),* Paper JWA55, 2011.

[19] L. H. Sahasrabuddhe and B. Mukherjee, "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," *IEEE Commun. Mag.*, vol. 37, pp. 67 – 73, Feb. 1999.

[20] R. M. Karp, Reducibility among Combinatorial Problems, R. E. Miller, J. W. Thatcher, Editors , *Complexity of Computer Computations,* Plenum Press, pp. 85–103, 1972.

[21] D.-N. Yang and W. Liao, "Design of Light-Tree Based Logical Topologies for Multicast Streams in Wavelength Routed Optical Networks," *IEEE International Conference on Computer Communications (Infocom)*, vol. 1, pp. 32-41, 2003.

[22] G. Sahin and M. Azizoglu, "Multicast routing and wavelength assignment in wide area networks," *in SPIE Proc. Conf. All-Optical Networking,* vol. 3531, pp. 196 – 208, Nov. 1998.

[23] B. Chen and J. Wang, “Efficient routing and wavelength assignment for multicast in WDM networks,” *IEEE J. Sel. Areas Commun.*, vol. 20, no. 1, pp. 97-109, Jan. 2002.

[24] X.-H. Jia, D.-Z. Du, X.-D. Hu, M.-K. Lee and J. Gu, “Optimization of wavelength assignment for QoS multicast in WDM networks,” *IEEE Trans. Commun.*, vol. 49, pp. 341 – 350, Feb. 2001.

[25] J. He, S.-H. Gary Chan and Danny H. K. Tsang, “Routing and wavelength assignment for WDM multicast networks,” *IEEE Global Telecommunications Conference (GLOBECOM)*, vol. 3, pp. 1536-1540, 2001.

[26] X. Zhang, J. Y. Wei and C. Qiao, “Constrained multicast routing in WDM networks with sparse light splitting,” *IEEE/OSA J. Lightw. Technol.*, vol. 18, pp. 1917 – 1928, Dec. 2000.

[27] S.-Y. R. Li, R. W. Yeung and N. Cai, “Linear network coding,” *IEEE Trans. Inf. Theory*, vol. 49, pp. 371–381, Feb. 2003.

[28] R. Ahlswede, N. Cai, S.-Y. R. Li and R. W. Yeung, “Network information flow,” *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204-1216, July 2000.

[29] A. E. Kamal, “OPN04-3: 1+N Protection in Mesh Networks Using Network Coding over p-Cycles,” *IEEE Global Telecommunications Conference (GLOBECOM)*, vol., no., pp.1-6, 2006.

[30] A. E. Kamal, “1+N Network Protection for Mesh Networks: Network Coding-Based Protection Using p-Cycles,” *IEEE/ACM Trans. Netw.*, vol. 18, no. 1, pp. 67-80, Feb. 2010.

[31] R. C. Menendez and J. W. Gannett, “Efficient, Fault-Tolerant All-Optical Multicast Networks via Network Coding,” *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper JThA82, 2008.

[32] K. Miller, T. Biermann, H. Woesner and H. Karl, “Network Coding in Passive

Optical Networks," *Proc. IEEE Int'l. Symp. Network Coding*, Toronto, June 2010.

[33] M. Belzner and H. Haunstein, "Network Coding in Passive Optical Networks," *IEEE/OSA European Conference on Optical Communication (ECOC)*, Paper P6.20, Sept. 2009.

[34] K. Fouli, M. Maier and M. Médard, "Network coding in next-generation passive optical networks," *IEEE Commun. Mag.*, vol. 49, no. 9, pp. 38-46, Sept. 2011.

[35] X. Liu, K. Fouli, R. Kang and M. Maier, "Network-Coding-Based Energy Management for Next-Generation Passive Optical Networks," *IEEE/OSA J. Lightw. Technol.*, vol. 30, no. 6, pp. 864-875, Mar. 2012.

[36] B. Skubic, J. Chen, J. Ahmed, L. Wosinska and B. Mukherjee, "A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON," *IEEE Commun. Mag.*, vol. 47, no. 3, pp. 40-48, Mar. 2009.

[37] S. Zhang, S.-C. Liew and P. P. Lam, "Hot topic: physical layer network coding," *in Proc. 12th MobiCom*, pages 358–365, NY, 2006.

[38] Y. Su, Y. Tian, E. Wong, N. Nadarajah and C. C. K. Chan, "All-optical virtual private network in passive optical networks," *Laser Photon.Rev.*, vol. 2, no. 6, pp. 460–479, Dec. 2008.

[39] C. J. Chae *et al.*, "A PON system suitable for internetworking optical network units using a fiber Bragg grating on the feeder fiber," *IEEE Photon. Technol. Lett.*, vol. 11, no. 12, pp.1686–1688, Dec. 1999.

[40] E. Wong and C.-J. Chae, "CSMA/CD-based ethernet passive optical network with optical internetworking capability among users," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2195-2197, Sept. 2004.

[41] N. Nadarajah *et al.*, "Novel schemes for local area network emulation in passive optical networks with RF subcarrier multiplexed customer traffic," *IEEE/OSA J. Lightw. Technol.*, vol. 23, no. 10, pp. 2974- 2983, Oct. 2005.

[42] Y. Tian *et al.*, “Demonstration and Scalability Analysis of All-Optical Virtual Private Network in Multiple Passive Optical Networks Using ASK/FSK Format,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 20, pp. 1595-1597, Oct. 2007.

[43] Q. Zhao and C.-K. Chan, “A Wavelength-Division-Multiplexed Passive Optical Network With Flexible Optical Network Unit Internetworking Capability,” *IEEE/OSA J. Lightw Technol.*, vol. 25, no. 8, pp. 1970-1977, Aug. 2007.

[44] Steven K. Korotky, “Traffic Trends: Drivers and Measures of Cost-Effective and Energy-Efficient Technologies and Architecture for Backbone Optical Networks,” *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, 2012.

[45] L. Kou *et al.*, “A fast algorithm for Steiner trees,” *Acta Informmarica*, vol. 15, pp. 141-145, 1981.

[46] R. Kubo, M. Tadororo, H. Nomura, H. Ujikawa, S. Nishihara, K. I. Suzuki and N. Yoshimoto, “Bandwidth Scheduling Techniques in TDM-PON Supporting Inter-ONU Communication with Network Coding for Smart Grid Applications,” *IEEE International Conference on Communications (ICC)*, June 2012.

[47] Z. X. Liu, M. Li, L. Lu, C. K. Chan, S. C. Liew and L. K. Chen, “Optical Physical-Layer Network Coding,” *IEEE Photon. Technol. Lett.*, vol. 24, no. 8, pp. 1424 – 1427, Sept. 2012.

[48] T. H. Wood *et al.*, “Observation of coherent Rayleigh noise in single-source bidirectional optical fiber systems,” *IEEE/OSA J. Lightw. Technol.*, vol. 6, no. 2, pp. 346 – 352, Feb. 1988.

[49] C. Su *et al.*, “Theory of burst-mode receiver and its applications in optical multiaccess networks,” *IEEE/OSA J. Lightw. Technol.*, vol. 15, no. 4, pp. 590-606, Apr. 1997.

List of Publications

Qike Wang and Lian-Kuan Chen, "Performance Analysis of Multicast Traffic over Spectrum Elastic Optical Networks", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OTh3B.7, 2012.

Zhixin Liu, Jing Xu, **Qike Wang** and Chun-Kit Chan, "Rayleigh Noise Mitigated 70-km-Reach Bi-directional WDM-PON with 10-Gb/s Directly Modulated Manchester-duobinary as Downstream Signal", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OW1B.2, 2012.

Qike Wang, Kam-Hon Tse, Lian-Kuan Chen, Soung-Chang Liew, "Physical-Layer Network Coding for VPN in TDM-PON", submitted to *Photonics Technology Letters, IEEE*, 2012.