### SDN-Enabled Dynamic Feedback Control and Sensing in Agile Optical Networks

by

Likun Lin

Copyright © Likun Lin 2016

A Thesis Submitted to the Faculty of the

COLLEGE OF OPTICAL SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2016

#### STATEMENT BY AUTHOR

The thesis entitled SDN-Enabled Dynamic Feedback Control and Sensing in Agile Optical Networks prepared by Likun Lin has been submitted in partial fulfillment of requirements for a master's degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that an accurate acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the copyright holder.

SIGNED: Likun Lin

#### APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

John W. Wissinger Research Professor of Optical Sciences <u>May 9, 2016</u> Date

## Contents

A	ABSTRACT			
1	Introduction9			
	1.1	Em	erging Traffic Pattern9	
	1.2 Agile Optical Networks		le Optical Networks	
	1.3	Key	7 Technologies for Agile Optical Networks	
	1.3.	1	Flexible Optical Network14	
	1.3.	2	Unified SDN Control Plane	
	1.3.	3	Real-time Sensors for Optical Link	
	1.4	Sco	pe of Thesis17	
2	Ext	ende	d SDN Control Plane for Agile Optical Networks19	
	2.1	Ove	rview of SDN Control Plane Architecture19	
	2.2	Glo	bal Controller: Extended SDN Controller Ryu22	
	2.2.	1	Architecture Extension on Global Controller22	
	2.2.	2	SDN Controllers Comparison24	
	2.2.	3	OpenFlow Protocol Extension26	
	2.3	Dor	nain Controller	
	2.4	Cor	clusion	
3	Rea	l-tim	e Cross-layer Impairment-aware Protection35	
	3.1	The	Concept and Novelty of Cross-layer Protection35	
	3.2	DL	I-based OSNR Monitor	
	3.3	Fun	ctional Diagram and Algorithm37	
	3.4	Exp	eriment Validation	
	3.4.	1	ROADM-based Multi-layer Networks Testbed40	
	3.4.	2	Shortest End-to-End Traffic Path Provision	
	3.4.	3	Dynamic Cross-layer Traffic Protection	
	3.5	Cor	clusion	
4	Adv	vance	ed Distance-Adaptive Spectrum Allocation in OFDM Network	
	4.1	Rea	ch Problem Analysis	
	4.1.	1	Challenge for High Capacity Transmission	
	4.1. Imp	2 prove	Off-line Distance-adaptive Modulation Assignment for Spectral Efficiency ment	
	4.1.	3	Differential BER Penalty across Single Channel in ROADM Networks	

4.2 Pr	oposed Approach	51
4.2.1	OSNR Network Model for Link Analysis	52
4.2.2	Adaptive Modulation Assignment to Overcome Narrowing Effect	55
4.3 Ex	periment	58
4.3.1	Network Elements Characterization	58
4.3.2	Back-to-Back System OSNR Versus BER Curve for OFDM signals	60
4.3.3	Experimental Validation	64
4.4 Re	sults and Discussions	68
5 Conclu	sion	71
5.1 Contr	ibution Summary	71
5.2 Futur	e Work	71
References.		73

# List of Figures

Figure 1.1 Total IP traffic growth trend at the CAGR of 23%, 2014-2019, forecasted by Cisco
(adapted from [42])
Figure 1.2 Global metro traffic compared to long-haul traffic, 2014 and 2019, forecasted by
Cisco (adapted from [42])
Figure 1.3 Global DC traffic growth trend at the CAGR of 23%, 2014-2019, with the majority of
traffic remaining in the inter center forecasted by Cisco (adapted from [44])
Figure 1.4 Busy-hour traffic grows faster than the average-hour traffic (adapted from [42]) 11
Figure 1.5 Closed-loop feedback control concept for dynamic resource allocation in
communication networks
Figure 1.6 An example of achieving additional spectrum saving by migrating ITU-T fixed grid
network in (a) to the flexible grid network in (b) (adapted from [6])
Figure 1.7 SDN concept of decoupling control plane from data plane (adapted from [38]) 16
Figure 2.1 The concept diagram of the centralized SDN control plane
Figure 2.2 The concept diagram of distributed SDN control plane
Figure 2.3 Hierarchical SDN control concept including local controllers to fast deal with frequent
events and global controller to make an overview network decision
Figure 2.4 Implemented SDN control plane
Figure 2.5 The architecture of Rvu controller for electrical packet network
Figure 2.6 The architecture of extended Rvu controller by adding the software components.
interfaces and protocols for optical transport network
Figure 2.7 The procedure of setting up connection and configuring optical network
Figure 2.8 The structure description of OpenFlow message header
Figure 2.9 Optical network resources collection procedures after the handshake
Figure 2.10 The description of the topology message structure
Figure 2.11 The header structure of OFPT_WAVEPLAN_REPLY with ID fields to indicate the
optical device
Figure 2.12 The concept of encoding the central frequency and bandwidth using the slot width in
flexible grid network
Figure 2.13 The payload structure of OFPT_WAVEPLAN_REPLY with the slot value and the
slot plan
Figure 2.14 Controller sends down the network actions to allocate network resources through the
CFLOW_MOD after handshake and resources collection
Figure 2.15 The action payload for EDFA to tune the gain
Figure 2.16 The internal design of domain controller consisting of CDPI and FPGA to provide
fast command execution on optical devices
Figure 3.1 The concept diagram of SDN-based cross-layer feedback control
Figure 3.2 The schematic of DLI-based OSNR monitor
Figure 3.3 Functional diagram of cross-layer protection in the extended SDN controller
Figure 3.4 The description of RWA algorithmError! Bookmark not defined.
Figure 3.5 ROADM-based metro network
Figure 3.6 The architecture of a 4-degree CDC ROADM

Figure 3.7 Shortest end-to-end traffic path provision under the extended SDN control plane through OF. 1.3+
control plane with the assistance of OPM45
Figure 4.1 Trade-off between optical reach distance and spectral efficiency (adapted from [46])
Figure 4.2 Constellation gets tight with the increase of modulation order (adapted from [46]) 49
Figure 4.3 The concept of distance-adaptive spectrum allocation mechanism (adapted from [25])
Figure 4.4 Narrowing effect through ROADMs 51
Figure 4.5 Noise components in the optical channel (adapted from [30])
Figure 4.6 Modules design of network model
Figure 4.7 Multi-modulation formats loaded in the OEDM signal each color presents one
modulation format
Figure 4.8 Eurotional block diagram for adaptive modulation assignment running in the
analization layor
Eigene 4.0 Experimental actual for macauning the OSNDs at a sints A and D using OSA
Figure 4.9 Experimental setup for measuring the OSNRs at points A and B using OSA
Figure 4.10 OSNR measurement in OSA using the interpolated method (adapted from [36]) 59
Figure 4.11 Back-to-Back measurement system setup
Figure 4.12 OFDM receiver analyzing the BER
Figure 4.13 Back-to-Back OSNR vs. BER curve for mixed modulation schemes QPSK and
BPSK in three subcarrier groups
Figure 4.14 Experimental setup of 4-span network to study the narrowing effect
Figure 4.15 Spectral efficiency improvement for the proposed advanced modulation assignment
mechanism over the existing technique
Figure 4.16 The estimation results of two network models compared to the correct estimation
zone, showing the enhanced network model can improve the estimation accuracy: (a) signal is
transmitted to ROADM 4, (b) signal is transmitted to ROADM 3, (c) signal is transmitted to
ROADM 2

## ABSTRACT SDN-Enabled Dynamic Feedback Control and Sensing in Agile Optical Networks

### by Likun Lin

Fiber optic networks are no longer just pipelines for transporting data in the long haul backbone. Exponential growth in traffic in metro-regional areas has pushed higher capacity fiber toward the edge of the network, and highly dynamic patterns of heterogeneous traffic have emerged that are often bursty, severely stressing the historical "fat and dumb pipe" static optical network, which would need to be massively over-provisioned to deal with these loads. What is required is a more intelligent network with a span of control over the optical as well as electrical transport mechanisms which enables handling of service requests in a fast and efficient way that guarantees quality of service (QoS) while optimizing capacity efficiency.

An "agile" optical network is a reconfigurable optical network comprised of high speed intelligent control system fed by real-time in situ network sensing. It provides fast response in the control and switching of optical signals in response to changing traffic demands and network conditions. This agile control of optical signals is enabled by pushing switching decisions downward in the network stack to the physical layer. Implementing such agility is challenging due to the response dynamics and interactions of signals in the physical layer. Control schemes must deal with issues such as dynamic power equalization, EDFA transients and cascaded noise effects, impairments due to self-phase modulation and dispersion, and channel-to-channel cross talk. If these issues are not properly predicted and mitigated, attempts at dynamic control can drive the optical network into an unstable state.

In order to enable high speed actuation of signal modulators and switches, the network controller must be able to make decisions based on predictive models. In this thesis, we consider how to take advantage of Software Defined Networking (SDN) capabilities for network reconfiguration, combined with embedded models that access updates from deployed network monitoring sensors. In order to maintain signal quality while optimizing network resources, we find that it is essential to model and update estimates of the physical link impairments in real-time.

In this thesis, we consider the key elements required to enable an agile optical network, with contributions as follows:

- **Control Framework**: extended the SDN concept to include the optical transport network through extensions to the OpenFlow (OF) protocol. A unified SDN control plane is built to facilitate control and management capability across the electrical/packet-switched and optical/circuit-switched portions of the network seamlessly. The SDN control plane serves as a platform to abstract the resources of multilayer/multivendor networks. Through this platform, applications can dynamically request the network resources to meet their service requirements.
- Use of In-situ Monitors: enabled real-time physical impairment sensing in the control plane using in-situ Optical Performance Monitoring (OPM) and bit error rate (BER) analyzers. OPM and BER values are used as quantitative indicators of the link status and are fed to the control plane through a high-speed data collection interface to form a closed-loop feedback system to enable adaptive resource allocation.
- **Predictive Network Model**: used a network model embedded in the control layer to study the link status. The estimated results of network status is fed into the control decisions to precompute the network resources. The performance of the network model can be enhanced by the sensing results.
- **Real-Time Control Algorithms**: investigated various dynamic resource allocation mechanisms supporting an agile optical network. Intelligent routing and wavelength switching for recovering from traffic impairments is achieved experimentally in the agile optical network within one second. A distance-adaptive spectrum allocation scheme to address transmission impairments caused by cascaded Wavelength Selective Switches (WSS) is proposed and evaluated for improving network spectral efficiency.

## **1** Introduction

### **1.1 Emerging Traffic Pattern**



Figure 1.1 Total IP traffic growth trend at the CAGR of 23%, 2014-2019, forecasted by Cisco (adapted from [42])

Table 1.1 Global IP traffic explosion in the past two decades (adapted from [42])

Year	Global Internet Traffic
1992	100 GB per day
1997	100 GB per hour
2002	100 GBps
2007	2000 GBps
2014	16,144 GBps
2019	51,794GBps

Source: Cisco VNI, 2015

Global IP Traffic has experienced an exponential rate growth in the past two decades; growing from 100 GB per day in 1992 to 16,144 Gbps in 2014, (table 1.1). This growth rate is forecasted to continue with the rapid increasing of internet devices, highly volume video and other bandwidth demand applications [42]. A recent traffic report from Cisco forecasts total IP traffic will increase

at a compound annual growth rate (CAGR) of 23% from 2014 to 2019 as shown in figure 1.1. The total IP traffic is forecast to reach 2 zettabytes [zeta =  $10^{21}$ ] per year as in 2019.



Figure 1.2 Global metro traffic compared to long-haul traffic, 2014 and 2019, forecasted by Cisco (adapted from [42])

Metro-only traffic has been the dominant contribution to this traffic growth compared to long-haul traffic which has grown more slowly. Metro-only traffic surpassed the long-haul traffic in 2014 (figure 1.2) and is forecasted to grow at twice the rate of long-haul traffic from 2014 to 2019 [42]. IP video and the Data Center (DC) traffic are the main drivers for the dramatic growth of metro traffic [43].





Figure 1.3 Global DC traffic growth trend at the CAGR of 23%, 2014-2019, with the majority of traffic remaining in the inter center forecasted by Cisco (adapted from [44])

On demand video, which provides customers to flexibly access the video services at anytime and anywhere rather than having to watch at a specific broadcast time, consumes a significant portion of IP video traffic and is forecasted to reach 80% of total traffic by 2019 [42]. The on demand video with the features of short-lived and heterogeneous evolves the traffic pattern to be dynamic. The global DC traffic is forecasted to grow at 25% CAGR and reach to 10.4 ZB per year in 2019 [44]. A majority (over 70%) of the global DC traffic remains in the data center. Much of this interdata center traffic has requires the rapid transfer of large amounts of data resulting in a "bursty" traffic pattern. This bursty pattern can involve transfers ranging from several terabytes to petabytes [45].



Figure 1.4 Busy-hour traffic grows faster than the average-hour traffic (adapted from [42])

The study on traffic trends also shows that the busy-hour Internet traffic is increasing faster than the average-our Internet traffic in figure 1.4. The discrepancy between the busy-hour traffic and the average-hour traffic is increasing that results in the bursty traffic. Moreover, the increasing of the devices and connections to Internet brings a growing number of new applications. A continuing growth number of M2M applications including health monitors and smart meters will be 43 percent of the total devices and connections [42]. With these growing diverse applications connected to Internet, the traffic pattern becomes heterogeneous. Thus a network that can support the services to deal with these **dynamic**, **bursty and heterogeneous** traffics is desirable.

## **1.2 Agile Optical Networks**

In the current network, service delivery relies on the layer 2 to layer 4 packet switching between the electrical nodes. The role of existing optical network is to connect the electrical nodes and provide a fixed bandwidth service through provisioning a channel for the traffic [1]. Optical network resources are provisioned for peak or high traffic conditions with additional capacity for resiliency to further guarantee the signal quality [3]. Once the lightpath is setup, the optical resource remains in a static configuration until it is manually reconfigured. In the current paradigm, the optical network is treated as dumb pipes without any active switching to optimize the network resource utilization [1]. With the emerging dynamic and bursty traffic patterns, this existing overprovisioned network system endures significant capacity limitation due to the inefficient resource allocation. The motivation of utilizing network resources more customizable and elastic has driven the development of agile optical network [2]. Agile optical network is defined as an **intelligent**, **automatic** optical network that can in **real-time** dynamically **adapt physical aggregation network resources in response to** the rapid network channel conditions and demands in an **efficient** way. According to this definition, the agile optical network should have the following features:

- Cost-effective switching through moving switching from higher layer to optical transport layer
- Efficient resource utilization for dynamic wavelength services by flexible switching
- Allows resources to be remotely reconfigured dynamically in the underlying networks
- Real-time sensing technologies for network services to be aware of the network conditions

Pushing switching to the optical transport layer in order for active switching is a fundamental requirement for agile optical network and becomes achievable recently with the development of

Photonic technology. Optical resources are no longer static in the physical layer, but are made visible for network services to dynamically manage and adapt to the network conditions. Moreover, a more flexible switching architecture with adjustable wavelength, bandwidth and modulation formats is essential to meet the variety of traffic requirements as well as to improve network efficiency. A forwarding and switching plane that incorporates advanced transceivers and ROADMs is necessary to support the flexible optical switching capability.

The forwarding and switching plane can be composed heterogeneous components consisting of network elements from multiple vendors with distinct features, configurations and technologies. To fully exploit the optical resources for agile optical switching, a separation of control plane and forwarding plane is a favored network design for supporting multiple network domains and multiple transport technologies. A packet-optical control plane is needed to intelligently abstract the forwarding plane that allows network-platform-specific characteristics and differences [4]. Currently, there is not a well-defined and widely-accepted standard protocol to manage the optical transport network. The challenge of this control plane is to investigate a unified control protocol for both the electrical and optical network. Network applications efficiently request and dynamically allocate the network resources to this control plane via the well-defined network interfaces.

A separation design of control plane and data plane increases the difficulty for network services to realize the network status. Parameters like OSNR and BER that affect application performance are tied to the underlying network with the changing characteristic [4]. In order to effectively and efficiently adapt network resources to the network status, the network services must be aware of the network conditions in a fast way. The requirement for monitoring drives the development of real-time sensing technologies in agile optical network, which measures the network parameters for making network decisions. Building an underlying network with the sensors is thus necessary to achieve agile optical allocation.

The ultimate goal of agile optical networks is to achieve a closed-loop feedback dynamic control system as shown in figure 1.5 that can allow the automatic control plane, flexible optical switching and real-time sensors function together efficiently. The flexible aggregation network is managed by the intelligent control plane. The real-time sensors measure the parameters of optical network and feeds the data to the control layer. A corresponding action is sent down to the underlying

network for adapting the resource to the network status. The closed-loop feedback system efficiently guarantees the signal quality even under the circumstance of rapid varying network conditions.



Figure 1.5 Closed-loop feedback control concept for dynamic resource allocation in communication networks (adapted from [4])

## **1.3 Key Technologies for Agile Optical Networks**

### 1.3.1 Flexible Optical Network

Flexible optical network sets the stage to build the agile optical network by enhancing the agility of underlying infrastructure. In a flexible optical network, spectrum resources can be allocated in an elastic manner that the signal central frequency, bandwidth and modulation formats are adjustable to support the dynamic traffic demands [5]. The benefit of the flexible optical network is the improvement of the network spectral efficiency by utilizing the sparse spectrum resources compared to the fixed grid network typically with 50 GHz channel spacing. An example illustrates

the efficient resource allocation is shown in figure 1.6. The rigid resources allocation in fixed grid network for heterogeneous traffics with multiple data rates demands 10 Gbps, 40 Gbps and 100 Gbps causes the spectrum inefficiencies resulting in regions where the spectrum between the two channels are wasted. A flexible optical network with 6.25 GHz central frequency granularity fully utilizes the sparse spectrum with the bandwidth variable capability and saves the additional network spectrum.



Figure 1.6 An example of achieving additional spectrum saving by migrating ITU-T fixed grid network in (a) to the flexible grid network in (b) (adapted from [6])

To achieve the flexible optical networking, an architecture that supports the dynamic service provisioning and restoration is needed [7]. Reconfigurable optical add/drop multiplexers (ROADM) with the features of scalability and flexibility are the fundamental optical subsystems that offer the flexible switching capability.

A ROADM is the fundamental optical subsystem in transparent network that enables remote dynamic configuration of wavelengths. With the advantages of transparency, scalability, large capability, flexibility, it is the first choice in agile optical network [29].

The benefits of ROADM network is listed below:

- Agile configuration and automated provisioning in physical layer
- Support for new applications like flexible resource allocation and bandwidth on demand
- Reduce the operational expenditure (Opex) and capital expenditure (Capex) by moving functionality down to optical layer (A rule indicates that switching the traffic in the higher layer cost more per bit than in the lower layer in the OSI model.)

To achieve a cost-effective and automated network without manual intervention or rewiring, a colorless-directionless-contentionless (CDC) ROADM is required to efficiently add/drop wavelength or route the wavelength to any direction. Colorless means that any wavelength can be assigned to any port at the add/drop site. Directionless allows any wavelength to be routed to any direction. Contentionless addresses the blocking issue when two wavelengths of the same color converge to the same Wavelength Selective Switching (WSS) structure.

#### 1.3.2 Unified SDN Control Plane

SDN is a paradigm that separates the control plane and forwarding plane as shown in figure 1.7. This separation enables drastic reduction in the complexity of the control plane while increasing the programmability and extensibility of network control [40]. SDN control plane abstracts the forwarding plane and enables the remote network control for network operators. The operators can dynamically manage the forwarding plane using software modules running in the application layer through the well-defined interfaces [39]. OF is the standard protocol that executes the network management, which was initially designed to manage the electrical packet networks.



Figure 1.7 SDN concept of decoupling control plane from data plane (adapted from [38])

A unified SDN control plane is defined as an integrated platform of electrical packet and optical transport networks. It provides the seamless control capability for both the electrical packet and optical transport networks by leveraging the SDN technology. The concept of SDN has been extended to the optical transport network through OF protocol extension. Network resources in

agile optical networks can be managed remotely in a convenient and efficient way through the SDN control plane in order to provide full resource utilization for dynamic optical switching. Moreover, this unified SDN control plane provides a reactive approach for dynamic traffic trends by allowing the packet network to be operated jointly with the optical network [39].

#### **1.3.3 Real-time Sensors for Optical Link**

The decisions in dynamic network resource allocation in agile optical networks depend on the optical link status. The sensing technology offers the capability of link status awareness to facilitate the agile network decision making. Sensors are able to sense, measure, and gather information from the agile optical network and feed these information to the SDN control plane through a high-speed data collection interface to form a closed-loop feedback system to enable adaptive resource allocation in a fast and efficient manner [41].

The optical network link status can be determined by measuring or calculating the optical signalto-noise ratio (OSNR) and bit error rate (BER). OSNR is the ratio of signal power to the noise power and BER is the number of bit errors per unit time. In-situ Optical Performance Monitoring (OPM) measures the physical layer impairments using the index OSNR in a real-time manner without any OEO conversion. BER analyzer provides the accurate BER data of the signal at the receiver on-the-fly. Using in-situ Optical Performance Monitoring (OPM) and BER analyzers in the control plane enables the real-time awareness of physical layer impairments in the optical link, thus to provide a closed-loop feedback system for agile optical network.

#### **1.4 Scope of Thesis**

This thesis investigates the required elements to build a closed-loop feedback dynamic control system for enabling the agile optical network: a) an extended SDN control plane framework for network remote control, b) the flexible optical network to provide active signal control and c) real-time sensors to measure the physical link status and feeds the measurement to the control plane.

In chapter 2, an extended SDN control plane is built upon the existing SDN control framework by adding the network management modules, interfaces and library parsers for optical network. This work spans the OF protocol to Optical Transport Network (OTN), thus provides the management capability for aggregation networks.

After building the closed-loop feedback dynamic control system, we studied two technologies to demonstrate the dynamic resource allocation in agile optical network: a) real-time cross-layer impairment-aware switching scheme for traffic protection and b) advanced distance-adaptive spectrum allocation to improve spectral efficiency.

Physical layer impairments in the optical link is invisible until the signal reaches to receiver and would significantly degrade the signal quality in the agile optical network. To maintain the signal quality in the optical link, this work introduces a cross-layer network traffic protection by leveraging the in-situ Optical Performance Monitoring (OPM) to real-time aware of the state of physical layer. The extended SDN control plane provides the optical signal control through the OF protocol extension. This work is discussed in the chapter 3.

In agile optical network, physical layer impairments and other network issues such as narrowing effect highly limits the optical reach distance and the network spectral efficiency. A distance-adaptive spectrum allocation mechanism is proposed in chapter 4 to address the optical reach problem coupled with the narrowing effect issue, thus to improve the spectral efficiency. A predictive network model is deployed to estimate the network status which is fed into the control decisions to precompute the network resources. BER analyzer in the receiver updates the actual link states to the controller for making optimized network decision.

## 2 Extended SDN Control Plane for Agile Optical Networks

This chapter introduces a hierarchical SDN control plane that expands the SDN intelligent control concept to optical transport layer by extending the southbound OF protocol 1.3. The purpose is to converge the control of electrical and optical networks, thus to build a scalable and extensible control framework in order to demonstrate the enabling technologies in agile hybrid networks in an efficient and standard way.

### 2.1 Overview of SDN Control Plane Architecture

One of the innovations implemented in the SDN is to separate the control and data planes. This separation allow the system to remove the complex control from the network devices [8]. The initial implementation of SDN work deploys a single controller in the control plane as shown in figure 2.1 [9]. The design of the single controller can fully utilize the network resources for making network decisions since it directly communicates with the data plane. However, this single controller design has a potential overloading issue in the control plane. The single controller needs to deal with all the network events including the frequent and resource-exhaustive events which introduce a great communication overhead and challenge the CPU capacity of the single controller. This overloading issue in the control plane significantly limits the network scalability that the single controller is not able to handle the growing amount of network [10, 11].



Figure 2.1 The concept diagram of the centralized SDN control plane



Figure 2.2 The concept diagram of distributed SDN control plane

To deal with this scalability limitation issue, researchers have studied the distributed SDN control plane (figure 2.2) which supports intra-domain control that reduces the pressure on every domain controller which improves the network scalability and resiliency [10, 12, 13]. However, each physical domain information is only accessible to its domain controller that decreases the centralized control capability. Although inter-domain communication mechanism between domain controllers has been proposed [14] to exchange domain information, it increases the control plane complexity and the latency.

Having a scalable control plane without losing centralized control capacity has attracted the interest of many research groups. The hierarchical control plane has been developed to meet this requirement as shown in figure 2.3. This architecture features distributed domain controller which functions as the local controller to manage the frequent event and a centralized controller to handle rare events [10]. In this hierarchical design, the domain controller is responsible for the domain network operation, and reports the network resource and status to global controller, which allows network scalability. The global controller has the overview across the whole network and is able to optimize the network efficiently.



Figure 2.3 Hierarchical SDN control concept including local controllers to fast deal with frequent events and global controller to make an overview network decision

The most important function of the SDN control plane driver is to provide an evaluation framework to study the system application as well as to meet the industrial requirement of network scalability and further integration. Thus, a hierarchical control plane has been built with an extended Ryu controller, a field-programmable gate array (FPGA) as global controller and local controller respectively as shown in figure 2.4.

This novel control plane architecture is based on an extended SDN global controller, running an enhanced version of OF 1.3 that spans optical transport. It includes a global network controller sitting on the top of network and distributed FPGA domain controllers for fast command execution. OF 1.3 protocol extensions to optical transport layer are integrated into SDN controller enabling the ability of control of packet and optical networks seamlessly. The electrical packet switches are directly managed by the global controller through OF 1.3. All the optical network devices can be fast controlled by the FPGA domain controllers in the millisecond level. The extended SDN controller is able to retrieve network resources stored in the domain controllers through oF protocol 1.3+ and make the optimal network action.

This SDN-based control plane enhances the agility of network by providing the capabilities of dynamic cross-layer protection and resource allocation through flexible wavelength assignment, adjustment of modulation schemes and smart passbands allocation based on real-time network

monitoring. More system applications can be studied in this control plane by leveraging its extended control framework and programmable infrastructure.



Figure 2.4 Implemented SDN control plane

### 2.2 Global Controller: Extended SDN Controller Ryu

#### 2.2.1 Architecture Extension on Global Controller

This work extends the SDN controller Ryu [15] to be a global controller of multilayer networks. Ryu is a SDN framework based on Python language running in the Linux system. It provides software components with well-defined APIs for network providers to easily manage the electrical packet network as shown in figure 2.5 [15]. Inside the framework, built-in applications, libraries and protocol parser work jointly to abstract the electrical network for the application layer and maps the network decisions of the applications to the network resources. The APIs provide a standard and efficient way for the framework to interact with the northbound network applications. The network application can easily access the network information or send down the network decisions through the APIs. In the southbound direction, the control plane communicates with the underlying network though the network protocols, which are the southbound interfaces. OF protocol is the widely used network protocol that was originally built for packet networks. It is an open standard that provides the management on the commercial Ethernet switches, routers and wireless access point. OF protocol defines messages such as packet-received and send-packet-out to support the communication between the OF switch and controller [28].



Figure 2.5 The architecture of Ryu controller for electrical packet network

In order to converge packet-optical network platform, this thesis spans the SDN concept to the optical transport network. A modified Ryu controller architecture was created by adding the software components, interfaces and protocols for optical transport network is shown in figure 2.6. This extended global controller parallels the packet and optical network management. The initially built-in apps on the left hand site manage the packet switches while the added apps on the right hand site deal with the optical networks events. Two parts of apps functions together to provide a unified platform for management on electrical and optical networks seamless.

This global controller uses the OF protocol 1.3+ as an optical network interface to retrieve the optical network resources and topology for upper layer framework and application service and executes the required actions on the optical network (section 2.2.3). Inside the framework, we built the optical network managers for discovering the network topology and resources including available link wavelengths and the characteristics of optical devices etc. This network system abstraction is provided via the northbound APIs to the application service.



Figure 2.6 The architecture of extended Ryu controller by adding the software components, interfaces and protocols for optical transport network

### 2.2.2 SDN Controllers Comparison

There are multiple widely-used SDN controllers including Ryu, Floodlight and OpenDayLight that all provide suitable platforms for the network management experiments. However, these SDN controllers have different designs, architectures, and interfaces. The selection of the SDN controller that fits the requirements of the research/application would dramatically reduce the time to implement the proposed improvements. This section compares some widely-used SDN controllers from a developer's perspective to look for a SDN controller with simple extended architecture and friendly interface for implementing the architecture extension.

	Deserve	et a substation	NOV	DVU	On an Daultak	01105
	Beacon	Floodlight	NOX	RYU	OpenDaylight	ONOS
First Release Date	9/12/2011	1/3/2012	5/11/2012	6/29/2012	12/9/2013	12/5/2014
Last Release Date	9/12/2013	8/2/2013	5/11/2012	11/1/2014	9/24/2014	
Language	Java	Java	C++	Python	Java	Java
Platform(s)	Linux	Linux/Win	Linux	Linux/Win	Linux/Win	N/A
Organization	Standford University	Big Switch	Nicira Networks	NTT	Industry supported	ON.LAB
Open Source	×		~	~	×	~
Design Intent	Designed to explore and demonstrate SDN potential	Commecial product with high performance	Designed to explore and demonstrate SDN potential	To provide a fully Opensource product for research perspectives	Commercial products to provide an industrial standard platform with: 1. High availability 2. High clustering 3. High security	Commercial products with: 1. High availability 2. High performance 3. Scale-out 4. Rich abstraction
Friendly developer-defined Applications	¥	~	<b>~</b>	~	×	N/A
OF 1.3	×	×	×	×	×	×
Southbound Multiprotocol	×	×	×	×	×	×
Virtualization	×	×	×	×	×	×
Supportive Documents and Tutorials					~	N/A
Active Community		~		×	×	N/A
Simple Architecture		~		×	×	×

Table 2.1 Comparison chart among the widely-used controllers

#### Note: This table was built in 2014.11.

The results of the SDN controller comparison are summarized in the table 2.1. The comparison first introduces the basic properties consisting of the release date, language, supported system platform and organization of the controllers. At this point, researchers can select a controller based on the language and platform preference. The design intent is a key factor that determines the performance of the SDN controller. Beacon and NOX are designed to demonstrate the SDN concept, thus have a relative poor performance on the scalability and security compared to the commercial products, especially OpenDayLight. However, there may be a trade-off between performance and friendly operation. OpenDayLight aims to provide an industrial platform with a variety of powerful tools and a multilayer architecture design inside the platform. This means a command must traverse multiple layers and interfaces from the application layer to the underlying network, which increases the complexity of running a northbound module and additional work for architecture extension. A controller with the simple layer architecture design like Floodlight and Ryu is a suitable option for the extension.

An OF protocol 1.3 supported controller is required in this extension because the protocol extension is based on this version (section 2.2.3). Beyond the design of the platform, having the support documents and tutorials and an active community significantly help researchers to understand the design in a quick way and save the time. Based on the selection criteria outlined above, the Ryu controller was selected for architecture extension because it supports the OF 1.3 protocol, has an extended simple architecture, and a friendly interface and the useful tutorials.

### 2.2.3 OpenFlow Protocol Extension

#### 2.2.3.1 Overview of OpenFlow Protocol Extension

This section introduces the OF protocol extension that allows the global controller to efficiently retrieve the underlying status of the network resources such as the optical switches, amplifiers and transceivers and execute network application actions. The ultimate goal of this extension is to integrate the SDN concept into the optical transport network and provide a unified control plane for packet and optical networks.

This extension targets the DWDM metro network with the focus to support the dynamic resource switching. The extension is based on the principle of the circuit flow table control mechanism first proposed in a protocol extension for TDM network [16]. Distinct from the OpenFlow packet table that mainly serves as lookup table, the circuit flow table presents the cross-connection with the signal information including the wavelength and bandwidth etc. inside the optical network. The circuit flow entry consists of the headers/identifiers and corresponding payloads/descriptive fields to set up a connection described in section 2.2.3.3.

Similar to the management of OF 1.3 for packet networks, this extension defines three types of new messages: handshake and configuration, optical network resource collection, and actions to support the optical network management. To keep the extension document consistent with the existing OF protocol document, the extension document describes the structure in the same way in OF protocol using the unsigned bit integer. The following sections describe the need for the new messages and part of their structures. For more details, please refer to the extension document [17].

#### 2.2.3.2 Handshake and Configuration





**Optical ROADMs** 

Figure 2.7 The procedure of setting up connection and configuring optical network

To manage the optical network, the controller should firstly set up the TCP connection with the domain controllers (section 2.3) sitting on the top of the network elements, retrieve the features of the network elements and configure the optical network using the new defined OF messages as shown in figure 2.7.

An OFPT\_CHELLO message containing only the OF header, which is the common header for every OF message, is used to set up the connection between controller and optical ROADMs. The description of the structure of the OF header is shown in figure 2.8. An 8 bit unsigned integer designates the OF protocol version published by Open Network Foundation (ONF), which supports up to 1.4. A following 8 bit unsigned integer and 16 bit unsigned integer represents the type and the length of the OF message respectively. The type value of OFPT\_CHELLO message is Ox53.

/* Header on all extended OpenFlow packets. */				
struct ofp_header {				
uint8_t version;	/* OFP_VERSION. */			
uint8_t type;	/* One of the OFPT_ constants. */			
uint16_t length;	<pre>/* Length including this ofp_cheader. */</pre>			
uint32_t xid;	/* Transaction id associated with this packet.			
	Replies use the same id as was in the request			
to facilitate pairing. */				
};				
OFP_ASSERT(sizeof(struct ofp_cheader) == 8);				

Figure 2.8 The structure description of OF message header

The feature and configuration messages are used to set up the working environment of the network. These messages are not used in the experiments described in thesis, and won't be discussed in this section. Please refer to the extension document for details.

#### 2.2.3.3 Optical Network Resources Collection



Figure 2.9 Optical network resources collection procedures after the handshake

After successfully setting up the connection and configuring the network, the controller starts to retrieve the optical network resources topology and wavelength plan (usable wavelengths). The messages OFPT\_TOPO\_REQUEST and OFPT\_WAVEPLAN\_REQUEST are used by the controller to request the optical network topology and wavelength plan respectively. These two messages do not contain a body beyond the OF header. The switch must report the network resources to the controller using the messages OFPT\_TOPO\_REPLY and OFPT\_WAVEPLAN\_REPLY per request. The procedure is shown in figure 2.9.

Optical network topology is formed of the optical links between any two adjacent ports. Message OFPT\_TOPO\_REPLY contains the optical link information for constructing the optical network topology. The optical link information is encoded by the lookup ID of two adjacent ports and fiber distance as shown in figure 2.10. Each lookup ID of one port contains its node/ROADM ID, network element ID, identity ID which is used to differentiate the same kind of elements and port ID. A 16 bit unsigned integer designates each ID and the length of the fiber. Each

OFPT\_TOPO\_REPLY contains all the internal links inside an optical node and the out-reach links from the node. Thus multiple OFPT\_TOPO\_REPLY messages may be needed to represent the whole optical network topology.

<pre>struct ofp_topo {</pre>		
uint16_t Node_ID;	/* The optical node's ID. */	
uint16_t Element_ID;	/* The network element's ID in this node. */	
uint16_t Identity_ID;	/* To differentiate the same kind of elements. */	
uint16_t Port_ID;	/* The output port's ID of the element. */	
uint16_t length;	/* The length between the two element. */	
uint16_t Node_ID;	/* The optical node's ID. */	
uint16_t Element_ID;	/* The network element's ID in this node. */	
uint16_t Identity_ID;	/* To differentiate the same kind of elements. */	
uint16_t Port_ID;	/* The input port's ID of the element. */	
};		
OFP_ASSERT(sizeof(struct ofp_topo) == 18);		

Figure 2.10 The description of the topology message structure

Optical network wavelength plan means the usable wavelengths in the optical links. In this extension, the available wavelengths of optical network devices are encoded in the message OFPT\_WAVEPLAN\_REPLY for controller to calculate the feasible wavelengths of the optical links, which are the common wavelengths of the two optical devices. By passing the complex calculation to the controller, each optical device updates its own wavelengths status without the need to consider the wavelengths in other devices. A header of the OFPT\_WAVEPLAN\_REPLY message consisting of ID fields indicates the specific optical device similar to OFPT\_TOPO\_REPLY as shown in figure 2.11.

struct ofp_waveplan_header {				
uint16_t Node_ID;	/* The optical node's ID. */			
uint16_t Element_ID;	/* The network element's ID in this node. */			
uint16_t Identity_ID;	/* To differentiate the same kind of elements. */			
};				
OFP_ASSERT(sizeof(struct ofp_waveplan_header) == 6);				

Figure 2.11 The header structure of OFPT\_WAVEPLAN\_REPLY with ID fields to indicate the optical device

In the payload of the OFPT\_WAVEPLAN\_REPLY message, the central frequency, bandwidth of the wavelengths are indicated by the slot width, which is the minimum passband of the WSS. Here is an example to illustrate this design concept as shown in figure 2.12. The slot width is

6.25 GHz. Since the C-Band range is from 195.9 THz to 192.1 THz, there are 608 slots in this range. The bandwidth of the wavelength is the total assigned slot width for the traffic while the central frequency is in the midpoint of the slots.



*Figure 2.12 The concept of encoding the central frequency and bandwidth using the slot width in flexible grid network* 

The payload of the OFPT\_WAVEPLAN\_REPLY message containing the fields of slot value and slot plan/slot status (open or closed) is shown in the figure 2.13. A 32 bit unsigned integer defines the potential slot values. Currently, the minimum slot value in this thesis is 6.25 GHz, thus a 608 bit unsigned integer is needed to tune the status of the 608 slots to get a desired central frequency and bandwidth.

/* Payload of the waveplan. */		
struct ofp_waveplan_payload {		
uint32_t slotvalue;	/* the value of the slot*/	
uint608_t slotplan;	/* tune the wavelength and bandwidth.*/	
};		
OFP_ASSERT(sizeof(struct	t ofp_waveplan_payload) == 80);	

Figure 2.13 The payload structure of OFPT\_WAVEPLAN\_REPLY with the slot value and the slot plan

#### 2.2.3.4 Network Actions



Figure 2.14 Controller sends down the network actions to allocate network resources through the CFLOW\_MOD after handshake and resources collection

Based on the collected resources, the controller is able to send down the circuit flow entries for setting up the cross-connection to provision or restore the network traffics as shown in figure 2.14. The circuit flow entry is encoded in the OFPT\_CFLOW\_MOD message. The ofp\_action is the key field in this message that indicates the port of the network device using the ID as illustrated above and defines the actions on it. The active devices in the experimental setup of this thesis are WSS, EDFA and transceivers. The action on transceiver is to tune the central frequency, bandwidth and modulation formats of the wavelength for supporting the flexible optical switching control. The action on WSS is to tune the status of its slot to either transmit or drop the signal. These two action messages has the same structure as the payload of the wavelength plan. The action on EDFA is to pick a desired gain to compensate the link loss as shown in figure 2.15.



Figure 2.15 The action payload for EDFA to tune the gain

## 2.3 Domain Controller



Figure 2.16 The internal design of domain controller consisting of CDPI and FPGA to provide fast command execution on optical devices

Domain controllers run at the local control plane layer between the global controller and the underlying network. Domain controller receives application requests from the global controller through the OF protocol 1.3+, to execute actions on the underlying domain network and report network resources back to the global controller. The internal design of domain controller is shown in figure 2.16, consisting of a control data plane interface (CDPI) and a field-programmable gate array.

CDPI is a software module running in the Linux system that functions as a protocol translator for OF protocol 1.3+ and Ethernet protocol that is used by FPGA. It enables the OF protocol control capability on the domain controller through protocol translation. CDPI also provides the network resources management through storing the optical network topology and wavelength plan.

A FPGA is a reprogrammable chip where the designer can develop digital computing tasks to implement hardware functionalities in a fast and reliable manner [37]. This work develops the fast control functionality of FPGA on the optical network devices including WSS, EDFA and Transceiver through the investigated interfaces which support multiple vendor specific protocols IIC, RS232, GPIB etc.

### 2.4 Conclusion

The work in this chapter builds an extended SDN control plane to provide the control capability of electrical and optical network resource seamless. We deployed a hierarchical SDN control plane architecture consisting of an extended Ryu controller running an enhanced version of OF protocol as global controller and FPGA-based domain controllers for fast command execution.

An extension on the Ryu framework by adding the optical network management modules and interfaces is successfully achieved. The extended SDN controller communicates with the optical network through the OF 1.3+ which defines the messages for optical resource management and optical signal control. The FPGA-based domain controller is implemented to provide the fast control and management in the millisecond level on the optical network devices. This extended SDN control plane is the fundamental work to facilitate the dynamic and remote control on the agile optical network.

## **3** Real-time Cross-layer Impairment-aware Protection

## **3.1** The Concept and Novelty of Cross-layer Protection



Figure 3.1 The concept diagram of SDN-based cross-layer feedback control

The cross-layer impairment-aware protection in this work means that extended SDN controller in layer 7 retrieves the parameter OSNR from optical transport layer with the assistance of SDN-enable OPM for making network decision to intelligently maintain the signal quality through the extended OF protocol as shown in figure 3.1. The extended SDN control plane (Chapter 2) enables the multilayer network management capability through unified OF 1.3.

Previous studies have shown the feasibility of using SDN controller to create and restore the endto-end cross-layer path [21]. However, their restoration is only applied to the case of link failure to simply switch the traffic to the other path. The more general case is that the signal quality is degraded but not failed is not considered in the previous studies. With the assistance of OSNR monitor, the restoration in this work is applied to the general case to improve the signal quality by adapting optical transceiver parameters such as modulation formats, bandwidth and wavelength. In the section below, we demonstrate the capability to adapt a clean wavelength to restore the signal when the physical layer impairments reach to unacceptable level

To the best of our knowledge, this is the first time any group has demonstrated the feasibility of SDN controller to adaptively control the ROADM and transceiver to maintain the signal quality

through the extended OF 1.3+. This approach simplifies the across layer control and provides a standard way of multilayer network management, which is the trend for next-generation network.

### **3.2 DLI-based OSNR Monitor**

The driver for the optical performance monitor is to detect the accumulated impairments in the optical transparent network. In the traditional opaque network, optical-electronic-optical (O-E-O) conversions are deployed at the switching and routing nodes to deal with impairments and to guarantee the signal quality to reach long distances [29]. In the transparent network, optical signal transmits though the network without any OEO conversion, which provides the advantages of high bandwidth capacity and resource allocation agility. However, the physical layer impairments in the transparent network are accumulated through the whole optical network and invisible until they reach the receiver for BER analysis. The accumulated impairments in the optical link may significantly distort the optical signal quality during transmission. It is desirable to perform real-time detection of these physical layer impairments in the optical link to maintain signal quality.

The optical signal-to-noise ratio (OSNR) is a key indicator of the state of optical network, which is desired in the DWDM network in order to be aware of the physical layer status thus to maintain the optical signal quality. In-situ Optical Performance Monitoring (OPM) has gained a lot of interests by potentially providing the OSNR measurement in a fast, cost-effective way without any OEO conversion.

This thesis implements the quarter bit delay line interferometer (DLI) based OPM as shown in figure 3.2. The optical signal goes through optical network system and is directed by an optical splitter to ONSR monitor. The monitor uses a bandpass filter (BPF) with a tunable passband to pick a desired channel, to filter the out-of-band noise. The filtered signal is passed to a delay line Mach-Zehnder interferometer, which provides a quarter-bit delay in one of the arm. Two ports with constructive and destructive output are generated as a result of interference and are measured by a dual power meter. The ratio of constructive power to destructive power approximates the OSNR. The accuracy of this OPM has been improved to achieve with <0.5 dB error for signals with up to 22 dB actual OSNR [19]. Moreover, research has demonstrated this OPM is able to enable the heterogeneous traffic by coming with a mapping table between OSNR and BER under different modulation formats [20].


Figure 3.2 The schematic of DLI-based OSNR monitor

This team has assembled an OSNR monitor and integrated it into a ROADM-based metro network system to enhance optical network intelligence. To leverage the OSNR monitor for real-time system operation under the SDN control plane, it is necessary to develop its control functionality to achieve a SDN-enabled OPM. This work has successfully investigated the python-based control interface on the passive device BPF and dual-channel power meter. The control modules are integrated into the same PC with the global controller using the serial protocol to retrieve measured powers periodically and configure the central wavelength and passband of the filter. The data can be received at the millisecond level if needed.

## 3.3 Functional Diagram and Algorithm

The cross-layer impairment-aware protection mechanism makes the decision highly dependent on the network resources (e.g. network topology and link status OSNR). To efficiently manage network data, especially for the large network, a well-designed functional diagram is needed. This work has implemented a functional block diagram of cross-layer network protection under the SDN control plane as shown in figure 3.3. All these modules reside in the SDN controller's service layer and can interact with the local controller through southbound OF protocol 1.3+. Each layer is briefly described as follows:



Figure 3.3 Functional diagram of cross-layer protection in the extended SDN controller

(1) Traffic Database (TD): This traffic database will update the network status (e.g. bandwidth utilization, existing wavelength routing path) and network topology in real-time. The information update will be triggered by Resource Provision Module (RPM).

(2) Resource Provision Module (RPM): Instructs the TD to update network status by receiving network status updates from local controller. This module also interacts with cross-layer optimization module (COM) and sends flow modifications to local controller.

(3) Network Abstraction Module (NAM): This module retrieves network's topology information from local controller, and abstracts the data plane for TD.

(4) Cross-layer Optimization Module: This module receives optimization task from Cross-layer Optimization Agent (COA) based on different objectives, then it performs a resource optimization based on the network status stored in TD. The resource optimization is stored in optical flow modifications and sent to RPM.

(5) Cross-layer Optimization Agent (COA): This agent invokes optimization objective either based-on manual input by the network operator (e.g. through web interface) or by automatically monitoring the network status (from TD). If it is based on network status monitoring, several thresholds should be set to invoke the optimization (e.g. maximum bandwidth utilization per port).

To implement this functional diagram, an event listener library has been used to send data or decisions between modules. Each module is triggered by an event to execute its function and returns the result to the next connected module.

Inside the COM, we investigates a physical layer impairment-aware Routing and Wavelength Assignment (RWA) algorithm using the first in first out (FIFO) system to calculate the clean wavelength as described below.

Physical-impariment aware RWA 1. Calculate k-shortest routes from Source to Dest, add them to a sorted set S #O(m + n log n + kn) m is toal edges, n is node
numbers
2. for each route r in S (loop 1)
for each candidate wavelength w in r (FIFO) (loop 2) #Check the OSNR reading v,assuming continous reading if v > th # that th is the OSNR threshold
assign w
end loop 1
end loop 2
else
continue
The algorithm worst case (Reach the end of loop) for step 2 would be O(kn)
The O(m + n log n + kn) + O(kn) = O(m + n log n + kn) In case of n = 4,m=6 and k = 3, the amount of time can be negligible

Figure 3.4 The description of RWA algorithm

## 3.4 Experiment Validation

#### 3.4.1 ROADM-based Multi-layer Networks Testbed

To demonstrate the cross-layer protection mechanism and deliver the programmable agile network, a ROADM-based hybrid electrical and optical metro-scale testbed is built as shown in figure 3.5. The OF-enabled packet switches connect to the user/server that forms the electrical network. The 10G on-off keying (OOK) transceiver followed by packet switch aggregates the electrical layer and optical transport layer. Four ROADMs with onboard Optical Performance Monitors for OSNR connect to each other that forming the optical network. Twelve EDFAs are deployed in the twelve optical links to compensate the power loss caused by the network devices.



Figure 3.5 ROADM-based metro network

The ROADM is the fundamental element in this metro network and it enables the optical switching capability to support the agile resource allocation in underlying network. Its architecture is shown in figure 3.6. It is a 4-degree node architecture with an add and drop site where a degree means a switching direction. Each ROADM has 6 transceivers at the add/drop site to generate and receive the optical signal. A 1 by 8 WSS is used to allocate resources to the correct transceiver. The other three degree each have a WSS to select the desired channels and send the signal to the destination. The WSS is the key component of ROADM. It provides the capabilities of switching and monitoring the wavelength and balancing the channel power across C-band through its internal Variable Optical Attenuator (VOA). Moreover, the Nistica WSS used in this setup breaks the spectrum down to 6.25 GHz granularities, which gives the CDC ROADM network flexible grid capability [22, 23].



Figure 3.6 The architecture of a 4-degree CDC ROADM

A hardware description in this setup is shown in table 3.1. All these passive components can be remotely controlled by the extended SDN controller through OF 1.3+. The metro testbed is a programmable network with the dynamic configuration capability provided by the ROADM. It provides the data plane functionalities to support the control plane OF Extension.

Component	Vendor	Quantity	Description
Electrical Packet Switch	Pronto	4	48 1Gb/s Ethernet ports and 4 10Gb/s optical ports (supporting 980nm, 1310nm, 1550nm)
			Per-channel attenuation,
1×8 WSS	Nistica	1×4=4	RS-232. USB and I2C interface with
1×4 WSS	Nistica	3×4=12	evaluation board
Evaluation Board of WSS	Nistica	4×4=16	Interfaces: USB, RS-232 and I2C
EDFA*	JDSU	3×4=12	Variable gain, High output power, RS-232 and I2C interface
Tunable Transceiver**	Finisar	6×4=24	Tunable wavelength on C-band
1×2 splitter(50/50)	Oplink	1×4=4	Connector type should be LC/UPC, Coupling ratio: 50/50, IL: 3.4 (dB)
1×3 splitter	Oplink	4×4=16	Coupling ratio: 33/33/33, IL: 5.5 (dB)
3×3 splitter	N/A	1×4=4	Coupling ratio: 33/33/33, IL: 5.5 (dB)

Table 3.1 Hardware description

This design has been shown to meet the power budget requirement as expected by successfully transmitting a signal through the multilayer system. The insertion loss from each device is the main contributor to the system loss. The requirement is to make sure in the worst case (i.e. consider highest loss on each device), the power on the Rx side should be above the minimum power. We use the following specifications as in table 3.2.

Device	Maximum Insertion Loss (dB)
1×2 WSS	5.6
1×4 WSS	9.0
1×8 WSS	10.0
$1 \times 2$ splitter (50:50)	Splitter: 3.3 Coupler: 0.3
1×3 splitter(33/33/33)	Splitter:5.5 Coupler: 0.8
EDFA	-22 (average)

Table 3.2 The insertion loss for each device, the negative sign means amplification

We consider the worst case with average amplification gain, which the transmitter carries lowest power -1dBm, and the sensitivity of receiver is -17dBm. In addition, each fiber optic adapter is considered 0.2dB each and traffic goes through 12 adapters on average, for a total of 2.4dB. For traffic in average, it should pass two  $3\times1$  and one  $2\times1$  coupler, two  $1\times3$  splitters, one  $1\times4$  WSS, one  $1\times8$  WSS, and one EDFA. The total loss would be 34.3dB and therefore the worst power of receiver would be -1dBm-34.3dB+22dB=-13.3dBm, which is above the threshold -17dBm. Note this only considers worst case for each device and the actual performance may be better.



#### 3.4.2 Shortest End-to-End Traffic Path Provision

Figure 3.7 Shortest end-to-end traffic path provision under the extended SDN control plane through OF 1.3+

In this experiment, we demonstrate the shortest end-to-end traffic path provision capability in a multilayer networks. This also shows the extended SDN controller can successfully manage the multilayer networks seamlessly through OF 1.3 and OF 1.3+. The multilayer networks control is the fundamental functionality of any system application.

As shown in figure 3.7, a server at the edge of Pronto Switch 1 starts streaming a high definition (HD) video using VLC media player to the client at the edge of Pronto Switch 2. The traffic packets are sent to the SDN packet switch 1, where it uses the packet handle mechanism of SDN controller. The SDN packet switch 1 searches its lookup table to match the packet fields of the first traffic packet. The SDN packet switch fails to match this packet fields and forwards this packet as OF Packet\_In message to the controller for disposition. The SDN controller decapsulates this packet to get the source and destination information carried in its header of packet switches for this traffic. From the figure 3.7, each packet switch is tightly coupled to one optical ROADM. The source and destination information of the packet switches actually indicate the input and output optical switch, which enables the SDN controller to calculate the shortest end-to-end path (i.e. 1->3) for the video

traffic based on the network topology. The controller executes RWA algorithm to set up a wavelength (FIFO, e.g. 1560.6nm) based on the wavelength capacity in this link. These actions are sent through OF Flow\_Mod messages to the packet switches and OF 1.3+ CFlow\_Mod messages to optical nodes including WSS and transmitters. Correspondingly, the packet switch 1 switches this traffic packets to the connected Finisar transceiver. The Finisar transceiver tunes the 10 G OOK wavelength and sends it to the optical network. The ROADM 1 sets up a lightpath to ROADM 3 for this 10 G OOK wavelength. The receiver followed by ROADM 3 transmits this optical wavelength back to electrical packets for the packet switch 3, which sends the packets to the client.



#### 3.4.3 Dynamic Cross-layer Traffic Protection

Figure 3.8 Dynamic cross-layer impairment-aware traffic protection under the extended SDN control plane with the assistance of OPM

In this experiment, we take a step further to demonstrate the dynamic cross-layer impairmentaware traffic protection. As shown in the figure 3.8, an end-to-end traffic path using wavelength  $\lambda_1$  is created through the multilayer networks. The OPM is integrated into ROADM 3 to measure in real-time the OSNR and feed this data to the extended SDN controller periodically (every 5 seconds). An amplified spontaneous emission (ASE) noise generator is deployed to emulate the physical layer impairments in the optical link. An in-band ASE noise for signal  $\lambda_1$  from noise generator is manually adjusted to degrade its OSNR below a preset threshold, which corresponds to the minimum acceptable signal quality. The unacceptable OSNR triggers the RWA algorithm to dynamically calculate a next available clean wavelength and passes the network decision through OF 1.3+ instructing the transceiver to tune the new wavelength and WSS to open slots for the new wavelength, restoring the signal quality. The total signal quality restoration time is less than one second. The main delay comes from the wavelength tuning in the transceiver.

## 3.5 Conclusion

Agile transparent optical network has accumulated and unpredictable physical layer impairments that significantly degrade the signal quality. DLI-based OPM provides a real-time physical layer impairments awareness for maintaining signal qualities. This work investigates the SDN control functionality on the OPM. The SDN-enabled OPM is integrated into a ROADM network under an extended SDN control plane to investigate the dynamic closed-loop feedback system for agile resource allocation. To enhance the underlying network agility, a CDC ROADM-based metro multilayer network is deployed to provide the fast and flexible switching capability.

This chapter demonstrates the multilayer network control capability of the extended SDN controller through provisioning an end-to-end traffic path. Moreover, dynamic cross-layer impairment-aware traffic restoration scheme has been successfully implemented to demonstrate the dynamic resource allocation technology in agile optical network within one second.

# 4 Advanced Distance-Adaptive Spectrum Allocation in OFDM Network

This chapter introduces an adaptive multiband modulation assignment scheme to overcome the transmission impairments with the emphasis on the cascaded WSS narrowing effect to improve the spectral efficiency in a reach OFDM network.

In the optical network, there is a trade-off between spectral efficiency (SE) and reach distance. The signals with high order modulation formats provide attractive spectral efficiency, but their reach distance is limited due to the fact it is sensitive to physical link impairments like chromatic dispersion and self-phase modulation etc. Previous research have demonstrated the offline adaptive modulation assignment in this reach problem by loading high order modulation format for short distance service request while low order modulation format for long distance [25].

However, we actually can take a step further to improve the SE by loading different modulation formats in one signal. This is because the edge of the signal contains more noise than the central part due the narrowing effect caused by the imperfect filter transfer function and frequency shift of the WSS. Once we have several cascaded WSS, the narrowing effect becomes significant. [27]

This work built a 4-span network WSS with EDFAs and 100 KM SMF fiber. On top of the testbed, there is a controller to optimize the network. In the controller, there is a network model to precompute the traffic pattern. In the receiver an oscilloscope could provide a BER analysis and feeds this data back to controller to take the corresponding action. The result shows that the spectral efficiency is improved by 66.7% when the traffic goes through 3 ROADM hops and 33.3% for 4 ROADM hops.

## 4.1 Reach Problem Analysis



#### 4.1.1 Challenge for High Capacity Transmission

*Figure 4.1 Trade-off between optical reach distance and spectral efficiency (adapted from [46])* 

The exponential growth in network traffic is driving the network service providers to offer high capacity transmission. With the existing well-utilized optical spectrum, improving the spectral efficiency is needed by adding bits to the available optical spectrum to increase the capacity. Spectral efficiency measures how efficiently the spectrum is being utilized [24].

However, increasing the spectral efficiency inherently decreases the optical reach distance limitation. Optical reach distance means the maximum distance that an optical signal can be transmitted without any OEO conversion. Signals are transmitted through the optical transmission system, where they accumulate noises due to the spontaneous emission noise of the EDFA and fiber impairments and etc. When the noises reach a point that the BER of signal is not acceptable, the signal needs to be regenerated. This point is called the optical reach distance limitation.

A trade-off between optical reach distance and spectral efficiency is summarized in figure 4.1. High order modulation format signals like DP-32 QAM and DP-64 QAM provide attractive spectral efficiency 5 bit/s/Hz and 6 bit/s/Hz respectively, but their optical reach distance are relative short around 400 and 200 km respectively. Signals with advanced modulation format is more susceptible to noises due to the fact that its constellation is more closely spaced compared to low order modulation formats as shown in figure 4.2.



Figure 4.2 Constellation gets tight with the increase of modulation order (adapted from [46])

In the current network, the modulation assignment mechanism is strongly limited by this trade-off. The optical system is designed to meet the worst situation requirement with only one signal modulation format given. Typically, the system assigns the modulation format required for the longest optical path which has the largest impairments to all the optical paths. Thus at the transmitter all paths occupy the same spectral width and modulation format regardless of the optical path length, which results in spectral inefficiencies [25].

## 4.1.2 Off-line Distance-adaptive Modulation Assignment for Spectral

#### **Efficiency Improvement**

To fully utilize network resources and improve the network spectral efficiency, researchers have presented an off-line distance-adaptive spectrum allocation as shown in figure 4.3. The concept is to save the assigned spectral resources for shorter paths by varying the number of modulated bits per symbol [25]. This technique exploits the trade-off between spectral efficiency and optical reach distance. It loads advanced order modulation format for short distance application and low order for long distance based on an off-line network model. One signal is loaded with one uniform modulation format.



Fig. 1. Principle of distance-adaptive spectral allocation in SLICE: a) multi-ring network with optical paths of different lengths; b) constellation diagrams with PolMux-QPSK format for longer path and PolMux-16QAM format for shorter path; c) optical spectrum of the respective paths.

Figure 4.3 The concept of distance-adaptive spectrum allocation mechanism (adapted from [25])

#### 4.1.3 Differential BER Penalty across Single Channel in ROADM Networks

WSS ROADMs are widely used as optical nodes to provide flexible switching capability in agile optical networks. The commercial WSS typically supports 50 GHz channel spacing for high speed 100 G transmission system. In DWDM system, WSSs are cascaded in the optical link together to support the dynamic service allocation. These successive WSSs significantly reduce the available optical passband caused by the filtering penalty, which is also known as narrowing effect. The filter passband is not perfectly flat and the central frequency of the filter has a shift that causes the progressive passband narrowing. With the increase in the number of filters, the penalty becomes significant. figure 4.4 shows the OSA measurement on the outputs from the cascaded WSSs and shows the narrowing effect issue. In this figure, the passband is defined as 3 dB loss bandwidth here.



Figure 4.4 Narrowing effect through ROADMs

Due to the narrowing effect, the signal is degraded differentially. The edge portion of the signal endure more filter penalty than the central parts. This causes a problem in that the BER performance is different across the single carrier signal. The traditional way of assigning an identical modulation format to the single carrier signal assumes all subcarrier groups have the same transmission degradation and occupy the same spectral width regardless of the subcarrier group location, which results in spectral inefficiency.

To solve the narrowing effect problem, researchers have has demonstrated the filter penalty could be reduced by adjusting the passband shape or introducing the loss ripple [26]. Researchers have also investigated an intelligent non-uniform passband assignment mechanism to reduce the narrowing effect and improve the BER performance [27]. In this thesis, we proposed an adaptive finer-granularity modulation assignment to dynamically deal with the narrowing effect issue while keeping the passband unchanged to save the network resource.

## 4.2 Proposed Approach

This work leverages the flexible spectrum allocation capability of the OFDM system to address the reach problem coupled with the narrowing effect. Here we proposed an OSNR network model to pre-compute the traffic resource and an advanced adaptive spectrum assignment mechanism to overcome physical layer impairments with the awareness of the narrowing effect.

#### 4.2.1 OSNR Network Model for Link Analysis

In the transparent optical networks, physical layer impairments are accumulated in the lightpath through the optical components including fiber, ROADM and EDFA. These impairments are invisible in the optical link until the signal is transmitted to the receiver for BER analysis. It is essential to detect the impairments in the optical link before reaching the BER distortion threshold.

As introduced in Chapter 3, the OSNR monitor provides a cost-effective way to measure the physical layer impairments by leveraging the delay-line interferometer. One disadvantage of this OSNR monitor is its coverage limitation that each monitor only provides an OSNR at the specific ROADM/node in the optical link. To fully know the network status at every node, ubiquitous OSNR monitors could be deployed in the optical network but this would dramatically increase the CAPEX. This section introduces a network model as an alternative way of estimating these accumulated impairments offline to support network resource allocation such as Routing and Wavelength Assignment (RWA). This network model is a database model that specifies the attributes of the network elements and system to analyze the signal quality at any nodes in the optical network without the coverage limitation.

The network model is well developed in the research and tends to be standard and commercial in industrial [18, 34, and 47]. Two kinds of network models are widely used: Optical to Signal Noise Ratio model and Q-factor ratio [29], which converts the physical layer impairments into index OSNR and Q-factor to estimate the quality of signal respectively. This work targets on a network model to analyze the link OSNR, which maps a corresponding BER information through an OSNR vs. BER mapping table (section 4.3.3). We adopted the impairments numerical analysis method from the book Advanced Optical Communication Systems and Networks [30] and proposed a basic OSNR network model and an enhanced OSNR network model according to the system characterization on OSNR in the OSA and BER analysis in the receiver respectively.

Physical layer impairments are diverse and complex [29]. Generally, physical layer impairments are categorized by linear and nonlinear impairments. The main physical layer impairments in the optical channel include the source noises from laser, the fiber modal noise, spontaneous emission noise and amplified spontaneous emission (ASE) noise generated by the amplifier, cross-talk due

to multiplexing and switching in ROADM and the thermal and dark noises caused by optoelectronic conversion in photodiode as shown in figure 4.5 [30].



Figure 4.5 Noise components in the optical channel (adapted from [30])

In our experiment (4.3.1) for demonstration purposes, only one channel is transmitted in the system, which mitigates the Four-wave mixing and cross-talk impairments. The single mode fiber (SMF) is deployed to eliminate the modal dispersion. As a result, our optical system consists of three impairments ASE, Chromatic Dispersion (CD) and Self-phase Modulation (SPM).

#### 1 ASE

The effective ASE noise penalty of the amplifier chain can be represented by effective noise figure.

$$NF_{eff} = NF_1 + \frac{NF_2}{G_1} + \frac{NF_3}{G_1G_2} + \dots + \frac{NF_k}{G_1G_2\dots G_{k-1}},$$
<sup>(1)</sup>

where NF is noise figure and G is the gain. The subscript stands for the order of the amplifier in the optical link.

#### 2 CD

The penalty caused by chromatic dispersion is:

$$\Delta P_{chrom} = 10 \log[\sigma_{chrom}/\sigma_0], \qquad \{2\}$$

where  $\sigma_0$  and  $\sigma_{chrom}$  are the root-mean-square (RMS) at the fiber input and output respectively.

$$\sigma_0 B \approx 0.177, \qquad \{3\}$$

$$\sigma_{chrom}^{2}(z) = \sigma_0^2 + (\beta_2 z/2\sigma_0)^2, \qquad \{4\}$$

where B, z and  $\beta_2$  are the data rate of the signal, the total fiber distance and the group velocity dispersion parameter that relates to the wavelength central frequency and chromatic dispersion coefficient below. The channels of interest are in the C-band which is far away from the zero-dispersion region, so we can neglect  $\beta_3$ .

$$\beta_2 = \frac{-D\lambda^2}{2\pi c},\tag{5}$$

3 SPM

The penalty caused by SPM is:

$$\Delta P_{SPM} = 10 \log \left[ \frac{\sigma_{SPM}}{\sigma_0} \right] = 10 \log \left( \sqrt{\left[ 1 + \frac{\sqrt{2}L_{eff}L\beta_2}{2L_{nel}\sigma_0^2} + \left( 1 + \frac{4}{3\sqrt{3}} \frac{L_{eff}^2}{L_{nel}^2} \right) \frac{L^2\beta_2^2}{4\sigma_0^4} \right]} \right), \quad \{6\}$$

where L,  $L_{eff}$  and  $L_{nel}$  are the total fiber distance, effective distance and nonlinear length that can be calculated below.

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha},\tag{7}$$

$$L_{nel} = \frac{1}{\gamma P_0},\tag{8}$$

Here  $\alpha$  is the loss coefficient.  $P_0$  is the launch power into the fiber and  $\gamma$  is the nonlinear efficient.

The basic OSNR network model considers only ASE because the OSNR degradation from CD and SPM is negligible according to the OSA measurements (section 4.3.1). However, all three impairments ASE, CD and SPM actually impact the BER performance. An enhanced version of OSNR network model is proposed to improve the network model accuracy on the BER calculation by considering the CD and SPM effects.

The OSNR model has been implemented into the controller based upon the design shown in figure 4.6. A traffic request with source and destination information triggers this sequence calculation of the network model. The first module shortest path calculation is to calculate the number of ROADMs in the optical link. The OSNR calculation model is based on the span of optical networks (section 4.3.1). With the ROADMs number, OSNR analysis module is able to calculate the number of span, amplifier and fiber length, thus to estimate the OSNR. In the modulation formats calculation module can retrieve the BER from this table. The other input to the modulation formats calculation module is the required BER which functions as the BER threshold. When allocating the modulation formats for the traffic, the modulation formats calculation module compares from the BER of the highest modulation formats to the lowest one

with the BER threshold until the analyzed BER is lower than the threshold. Finally, it sends the modulation formats decision.



Figure 4.6 Modules design of network model

### 4.2.2 Adaptive Modulation Assignment to Overcome Narrowing Effect

One of the limitations of the OSNR network model is that its accuracy highly depends on the status of the network components. Improving the accuracy of the network model requires the model to consider more physical layer impairments, which in turn increases the complexity. It is challenging for one network model to consider all the physical layer impairments to be exactly precise on its estimation. The problem of inefficient resource allocation or QoS guaranteed failure may be caused due to the imperfect performance of the network model.

To address this problem, a real-time adaptive resource allocation mechanism has attracted a lot of interests to optimize the network resources based on the dynamic network status with the assistance of the real-time sensing feedback technology. Even the off-line link analysis is not precise enough and the network link status fluctuates with the time, the adaptive mechanism is still able to correct the decision and guarantee the QoS and improve the traffic resource allocation efficiency. This adaptive control system is necessary for next-generation optical transmission network [31]. Many studies in the wireless network have proposed adaptive resource allocation to optimize the network parameters throughput, capacity and stability [31, 32, and 33]. Moreover, the parameters signal power, data rate, bandwidth and modulation scheme are adapted according to the changing network status [31]. In the paper [34], the researchers propose a resource allocation scheme to minimize transmit power for multicast orthogonal frequency division multiple access systems.



Figure 4.7 Multi-modulation formats loaded in the OFDM signal, each color presents one modulation format

This work proposes an advanced adaptive modulation assignment to improve the traffic resource allocation efficiency with the focus to address the narrowing effect issue. Compared to the existing technique (section 4.1.2), our proposed solution provides an on-line modulation scheme assignment according to the network status. Moreover, the modulation assignment in the existing technique is uniform for all subcarriers. However, as mentioned in section 4.3.1, the narrowing effect actually degrades the signal quality of subcarriers differently. The subcarrier groups on the edge of the signal has more degradation than the subcarrier groups on the central. In the existing technique, all subcarrier groups have the same transmission degradation and occupy the same spectral width regardless of the subcarrier group location, which results in spectral inefficient. The proposed modulation assignment scheme provides finer-granularity assignment as shown in figure 4.7. Instead of adapting the modulation scheme on the whole subcarriers of the traffic to the distance and network status, assigning the higher modulation format to the central subcarrier group and lower modulation format to the edge subcarrier group could improve the efficiency.



Figure 4.8 Functional block diagram for adaptive modulation assignment running in the application layer

To achieve the adaptive modulation assignment, a closed feedback functional block diagram of the controller is shown in figure 4.8. This functional block diagram has to meet two main requirements: 1) coordinate each part in a correct order, 2) build the data collection interface for BER. The procedure of this design is described below.

- a) A new traffic request triggers the network model to calculate the modulation formats based on the link analysis and the mapping table.
- b) Based on this calculation, the controller sends commands to the OFDM transceiver to provision the traffic resource.
- c) The OFDM receiver measures in real- the BER data of the traffic and feeds this data back to the controller. The controller determines either to trigger the adaptive modulation assignment or to wait for the new traffic based on the BER requirement.
- d) If the BER is not acceptable, the controller runs the adaptive modulation assignment algorithm to find the next optimized modulation formats until the BER meets the requirement.

## **4.3 Experiment**

#### 4.3.1 Network Elements Characterization

OSNR network model estimates the optical performance through the index OSNR according to the numerical analysis introduced in section 4.2.1. The correct decision of network resource allocation relies heavily on the accuracy of the estimation. This experiment measures the impact of network elements on signal OSNR using an Agilent Optical Spectrum Analyzer (OSA). The result is used to characterize the performance of network model.



Figure 4.9 Experimental setup for measuring the OSNRs at points A and B using OSA

The network elements in this experimental setup include WSS, EDFA and single mode fiber (section 4.3.3). We first measure the OSNR degradation independently of these three elements. An optical signal is sent through the device under test (DUT) as shown in figure 4.9. The OSNR degradation is the difference between the OSNR at point A and B as measured by OSA. The method of OSNR measurement with the OSA is to measure the signal power which is approximate the peak power and the noise power which is interpolated in each channel as shown in figure 4.10. In the figure,  $P_i$  is the optical signal power in watts at the i-th channel.  $N_i$  is the interpolated value of noise power in watts measured in noise equivalent bandwidth,  $B_m$ , at the i-th channel [36]. To improve the accuracy of the OSNR measurement, a combination of wide resolution bandwidth for signal and narrow resolution bandwidth for noise is used in this measurement [36].



Figure 4.10 OSNR measurement in OSA using the interpolated method (adapted from [36])

The OSNR can be calculated using the formula below according to the definition.  $B_r$  is the optical reference bandwidth, which is defined as 0.1 nm.

$$N_i = \frac{N(\lambda_i - \Delta\lambda) + N(\lambda_i + \Delta\lambda)}{2},$$
<sup>(9)</sup>

$$OSNR = 10\log\frac{P_i}{N_i} + 10\log\frac{B_m}{B_r},$$
<sup>(10)</sup>

The OSNR measurements are shown in the tables below. According to the measurement, we find that a) the insertion loss from WSS does not degrade OSNR, b) the effects of CD and SPM on OSNR can not be measured in the OSA, and c) the ASE generated by the EDFA impacts OSNR. The results matches to the basic OSNR network model under the allowing error.

Table 4.1 The measurement result on WSS

Study the effect of WSS on OSNR				
DUT	OSNR at A (dB)	OSNR at B (dB)	ΔOSNR (dB)	
one WSS	36.36	35.89	0.47	
two cascaded WSSs	36.36	36.21	0.15	
three cascaded WSSs	36.36	36.53	0.17	

Table 4.2 The measurement result on SMF

	Study the effect of SMF on OSNR			
DUT	OSNR at A (dB)	OSNR at B (dB)	ΔOSNR (dB)	
25 km SMF	36.36	35.99	0.37	
50 km SMF	36.36	35.77	0.59	
75 km SMF	36.36	35.96	0.4	

Study the effect of EDFA on OSNR, @gain = 15 dB					
DUT	OSNR at A (dB)	OSNR at B (dB)	∆OSNR (dB)		
one EDFA	44.67	36.64	8.03		
two cascaded EDFAs	44.67	34.69	9.98		
three cascaded EDFAs	44.67	33.37	11.3		

Table 4.3 The measurement result on EDFA

#### 4.3.2 Back-to-Back System OSNR Versus BER Curve for OFDM signals

Through analyzing the physical link impairments, the OSNR network model estimates the link index OSNR regardless of the modulation scheme. However, signal with distinct modulation scheme could have different quality even under the same OSNR performance. BER is the conclusive parameter to reflect the signal quality unconditionally (without the concern on the modulation scheme, bit rate and bandwidth). To have an estimated BER, the OSNR network model needs an OSNR versus BER curve to look up the BER.

Many researchers have studied the relationship between OSNR and BER for different modulation schemes. The theoretical results can be used to generate an OSNR versus BER curve which can be converted into a lookup table to generate BER information for network model. However, in this work, one OFDM signal is mixed with multiple modulation schemes which increases the complexity in finding the relationship between OSNR and BER. Alternatively, this work measures BER vs OSNR curve under the back-to-back system as shown in figure 4.10. The signal in the back-to-back system goes through less degradation since there is no impairments from fibers, EDFAs and ROADMs compared to the experimental system (figure 4.13). In this case, the OSNR has a much better performance. A noise emulator has been implemented in the back-to-back measurement setup for degrading the OSNR to a certain level that matches to the value in the real system. The noise emulator has a broadband amplified spontaneous emission noise source followed by an EDFA to amplify the noise power and a WSS to filter the noise on specific channel. The signal generated by the transceiver is coupled with the noise through a 50:50 optical coupler. 1% of the mixed signal is directed to the OSA for OSNR measurement and 99% is sent to the OFDM receiver for BER analysis. This configuration generates an OSNR and BER data pair. By changing the gain of the EDFA to adjust the noise level, additional data pairs are collected to form the OSNR versus BER curve.



Figure 4.11 Back-to-Back measurement system setup

For demonstration purposes, this work measures the combinations of coding two modulation formats QPSK and BPSK on three subcarrier groups. All the combinations are shown in table 4.4, where 1 and 2 represent BPSK and QPSK respectively according to the bit rate per symbol.

Subcarrier Group 1	Subcarrier Group 2	Subcarrier Group 3	Combination
1	1	1	111
1	1	2	112
1	2	1	121
1	2	2	122
2	1	1	211
2	1	2	212
2	2	1	221
2	2	2	222

Table 4.4 All possible combinations of coding BPSK and QPSK into three subcarrier groups

The OFDM signal is the double-side band signal where subcarrier group 1 is the central part while subcarrier group 3 is on the edge side. As a result, the degree of degradation increases from subcarrier group 1 to 3 due to the narrowing effect. Under the same network status and requirement, the combination "221" has a better BER performance than "212" and "122". And the spectral efficiency of these three combinations are equal under the fixed bandwidth, the controller chooses combination "221" among these three combinations. This choice rule also applies to the combinations "211", "121" and "112". Based on the analysis, an updated table in 4.5 is generated.

		0 00	
Subcarrier Group 1	Subcarrier Group 2	Subcarrier Group 3	Combination
1	1	1	111
2	1	1	211
2	2	1	221
2	2	2	222

Table 4.5 The selected combinations of coding BPSK and QPSK into three subcarrier groups due to narrowing effect

The BER analysis in the OFDM receiver is shown in figure 4.12. The receiver provides four BER values: the average BER of three subcarrier groups and each BER of three subcarrier groups in a few seconds denoted as  $BER_{av}$ ,  $BER_{group1}$ ,  $BER_{group2}$  and  $BER_{group3}$ . The BER results show that the central signal subcarrier group 1 has a better quality performance than the edge signal. Meanwhile, there is a constellation diagram to provide a visible view of the constellation status. The BER value is determined using the Error Vector Magnitude of the received constellation (which quantifies the quality of the received constellation) to calculate the BER instead of using bit counting [35]. The EVM method enables the system to measure very low BER values accurately within a short time.



Figure 4.12 OFDM receiver analyzing the BER

The curves of OSNR versus BER is plotted in figure 4.13. The range of OSNR is from 15 to 32 dB with step 1 dB for 15 to 26 dB where BER is sensitive to OSNR, and step 3 dB for 26 to 32 dB. BER reading is truncated below 1e-9 which is defined as error free and above 1e-2 which reaches the measurement accuracy limitation. The curves clearly show that advanced modulation scheme has poorer BER performance under the same OSNR requirement. Most importantly, varying the coding scheme in one subcarrier group could significantly change the BER performance, which supports the proposed modulation assignment scheme in section 4.2.2.



Figure 4.13 Back-to-Back OSNR vs. BER curve for mixed modulation schemes QPSK and BPSK in three subcarrier groups

#### 4.3.3 Experimental Validation



Figure 4.14 Experimental setup of 4-span network to study the narrowing effect

The experimental setup is shown in figure 4.14. A 4-span optical network is deployed into the back-to-back system setup (section 4.3.2) to emulate a metro optical network. The structure of a span includes an EDFA, a 25 km single-mode fiber (SMF) 28 and a WSS. Each EDFA provides gain range from 10 dB to 32 dB to compensate one span loss generated from the fiber and WSS. The WSS of the 4-span network supports the flexible grid capability with a passband granularity of 6.25 G. It has two outputs connected to the next span and WSS B. WSS B is used to select a channel from these four spans for BER analysis. This enables the automated control functionality for controller as well as improves the BER analysis accuracy by filtering the out-band noises before the photodiode. Beyond the 4-span network, the OFDM transceiver provides 12 G optical signal with 3 variable modulation formats BPSK, QPSK and 8 QAM. The experimental setup keeps the

noise emulator subsystem to vary noise level for studying the performance of adaptive modulation assignment mechanism and OSA to measure initial OSNR as an input to network model.

This experiment has two test cases to demonstrate: 1) the narrowing effect, 2) the traffic spectral efficiency improvement.

Test case 1: Narrowing Effect Verification

The first test case is to verify the narrowing effect as a function of two factors: passband and the number of cascaded WSSs in this 4-span optical network. This results will be assisted to select a suitable passband to demonstrate the adaptive modulation assignment. In this experiment, the controller sends out a 12 G optical signal with modulation combination '222' to the span network. WSS B picks up the signal from fourth WSS where the narrowing effect is expected to degrade signal quality significantly. The passband is varied from 25 G to 12.5 G for WSSs in the link while the incident signal power is kept the same level to the photodiode of the receiver by adjusting the gain of EDFA. This constant incident power makes the BER result comparable since BER is sensitive to the signal power.

A measured table is shown in table 4.6 where there are four BER data for each passband. The result shows that the narrowing effect happens from 25 G passband. With the passband gets narrower, the narrowing effect becomes severe, which matches to the simulation expectation. Based on this table, for demonstration purposes, we selected the 12.5 G passband for the link ROADMs because it showed the most significant degradation.

J						
	Combin	ation: '222'				
# WSS: 4						
Pout: 2.1 dBm						
Passband (G)	$BER_{av}$	$BER_{group1}$	$BER_{group2}$	$BER_{group3}$		
25	8.62E-07	1.50E-11	1.83E-08	2.57E-06		
18.75	6.86E-05	1.65E-09	3.02E-05	1.76E-04		
12.5	4.17E-04	2.77E-07	2.15E-04	1.00E-03		

 

 Table 4.6 Signal BER data for fourth cascaded WSSs under different passbands with fixed modulation formats combination and incident signal power to receiver

With fixed factor 12.5 G passband, the effect of second factor number of cascaded ROADMs on narrowing effect could be studied. In this experiment, the controller sends out a 12 G optical signal

with modulation combination '222' to the span network. WSS B picks signal from second, third and fourth ROADM each time for BER analysis. The result is shown in table 4.7. It shows that the BER performance degrades with the increase of cascaded WSS number which matches to the simulation result.

jormais combination and incluent signal power to receiver					
	Combin	ation: '222'			
Passband: 12.5G					
Pout: 2.1 dBm					
# ROADM	$BER_{av}$	$BER_{group1}$	$BER_{group2}$	$BER_{group3}$	
2	9.45E-06	1.45E-09	1.85E-06	2.65E-05	
3	6.28E-05	3.76E-09	1.48E-05	1.65E-04	
4	4.17E-04	2.77E-07	2.15E-04	1.00E-03	

 

 Table 4.7 Signal BER data for 12.5 G passband for different cascaded ROADMs with fixed modulation formats combination and incident signal power to receiver

Test case 2: Spectral Efficiency Improvement

This test case demonstrates the adaptive modulation assignment capability and compares the spectral efficiency under the proposed advanced distance-adaptive modulation assignment with the existing technique. In this experiment, traffic requests are from different WSS with BER requirement  $10^{-3}$  (assuming the system has forward error correction (FEC) technology) and the initial OSNR 33.2 dB.

When the signal transmits through 2-span network (two cascaded WSSs), the controller provisions a modulation combination "222" based on the estimation of basic network model. It turns out the BER meets the requirement (below 10E-3). The spectral efficiency of both the existing and proposed technique are 2 bit/s/Hz using the calculation formulas below.

$$Spectral Efficiency = \frac{bitrates}{bandwidth}$$
 {11}

Spectral Efficiency<sub>existing,2-span</sub> = 
$$\frac{(2 \times 4 + 2 \times 4 + 2 \times 4) \ Gbit/s}{12 \ GHz}$$
 {12}

$$=2\frac{bit}{s}/Hz$$

Spectral Efficiency<sub>proposed,2-span</sub> = 
$$\frac{(2 \times 4 + 2 \times 4 + 2 \times 4) \text{ Gbit/s}}{12 \text{ GHz}}$$

$$= 2 \frac{\text{bit}}{s} / \text{Hz}$$
(13)

When the signal transmits through 3-span network (three cascaded WSSs), the controller provisions a modulation combination "222" based on the estimation of basic network model. It turns out the BER can't the requirement. The controller runs the adaptive control algorithm to optimize the traffic. A modulation combination "221" is provisioned to meet the BER requirement. The existing technique would provision the modulation combination "111" in this case. The spectral efficiency of the existing and proposed technique are 1 bit/s/Hz and 1.67 bit/s/Hz respectively using the calculation formulas below.

Spectral Efficiency<sub>existing,3-span</sub> = 
$$\frac{(1 \times 4 + 1 \times 4 + 1 \times 4) \ Gbit/s}{12 \ GHz}$$

$$= 1 \frac{bit}{s} / Hz$$

$$(2 \times 4 + 2 \times 4 + 1 \times 4) \ Gbit/s$$

$$\{15\}$$

Spectral Efficiency<sub>proposed,3-span</sub> =  $\frac{(2 \times 4 + 2 \times 4 + 1 \times 4) \text{ dbit/s}}{12 \text{ GHz}}$ (13)

$$= 1.67 \frac{blt}{s}/Hz$$

When the signal transmits through 3-span network (three cascaded WSSs), the controller provisions a modulation combination "222" based on the estimation of basic network model. It turns out the BER can't the requirement. The controller runs the adaptive control algorithm to optimize the traffic. A modulation combination "211" is provisioned to meet the BER requirement. The existing technique would provision the modulation combination "111" in this case. The spectral efficiency of the existing and proposed technique are 1 bit/s/Hz and 1.33 bit/s/Hz respectively using the calculation formula below.

$$Spectral Efficiency_{proposed,4-span} = \frac{(2 \times 4 + 1 \times 4 + 1 \times 4) Gbit/s}{12 GHz}$$

$$= 1.33 \frac{bit}{s} / Hz$$

$$(16)$$

## **4.4 Results and Discussions**

This chapter investigates an advanced distance-adaptive modulation assignment control system to address the reach problem coupled with the narrowing effect issue. Subcarrier group-based modulation assignment mechanism is proposed to effectively solve the differential BER performance problem introduced by the narrowing effect. Two OSNR network models are proposed to estimate the link impairments for network traffic provision. On-the-fly BER analysis in the receiver enables the dynamic closed-loop feedback control capability to compensate the estimation errors from the network model and adapt to the network conditions.



Figure 4.15 Spectral efficiency improvement for the proposed advanced modulation assignment mechanism over the existing technique

Comparing the proposed advanced modulation assignment mechanism over the existing uniform modulation assignment technique, the spectral efficiency is improved 67% and 33% when the signal transmits through 3 and 4 cascaded WSSs respectively. Currently the trend of this improvement goes down in this figure but it could go up if two items are achieved: a) a better network environment through such as picking a wider passband or using an optimal signal power and b) a finer subcarrier group assignment and more modulation combinations. These two requirements together allow the controller to assign a higher order modulation formats with a finer subcarrier group modulation assignment. For example, there are 7 subcarrier groups and four kinds

of modulation formats BPSK, QPSK, 8-QAM, 16-QAM and 64-QAM. The modulation combination for the 3-span network under the existing and proposed technique are "3333333" and "5444433". The improvement of the spectral efficiency is 85.7%. The modulation combination for the 4-span network under the existing and proposed technique are "2222222" and "4333332". The improvement of the spectral efficiency is 100%. Thus the trend of this improvement is not fixed, instead it highly depends on the network environment, the available modulation formats and the number of subcarrier groups.







(b)

69



*<sup>(</sup>c)* 

Figure 4.16 The estimation results of two network models compared to the correct estimation zone, showing the enhanced network model can improve the estimation accuracy: (a) signal is transmitted to ROADM 4, (b) signal is transmitted to ROADM 3, (c) signal is transmitted to ROADM 2

To study the performance of network models, we compare their estimation OSNR with the correct estimation zone which is indicated by the accepted modulation combinations. The estimation point of the enhanced network model can be located in or always closer to the correct estimation zone as shown in figure 4.16. A table to summarize the result is shown in 4.8. An enhanced OSNR network model incorporating the CD and SPM impairments has shown to have higher estimation accuracy than the basic OSNR network model. However, since the enhanced network model doesn't consider all the impairments, thus it still have the estimation error.

 Table 4.8 Signal BER data for 12.5 G passband for different cascaded ROADMs with fixed modulation
 formats combination and incident signal power to receiver

Number of Cascaded WSSs	OSNR <sub>Estimation</sub> – OSNR <sub>Actual</sub>   <sub>min</sub> of Basic Network Model	OSNR <sub>Estimation</sub> - OSNR <sub>Actual</sub>   <sub>min</sub> of Enhanced Network Model
2	0 dB	0 dB
3	9 dB	0.5 dB
4	10 dB	0 dB

# 5 Conclusion

# **5.1 Contribution Summary**

This thesis builds a SDN-based closed feedback system with the assistance of the real-time sensing technology to facilitate the adaptive resource allocation in response to the rapid varying traffic pattern. The key elements to enable agile optical network in this control system includes: a) an extended SDN control plane for aggregation network management, b) the flexible optical networks with the OPM monitor on-board and BER analyzer in the receiver and c) a predictive network model and the resource allocation algorithms embedded in the control layer.

Under this feedback control system, we propose two adaptive resource allocation technologies to address problems in the agile optical network: a) a real-time cross-layer physical layer impairmentaware protection scheme that enables awareness of the physical layer impairment for traffic restoration to maintain the signal quality level and b) the advanced reach-adaptive modulation allocation for solving the combined optical reach problem narrowing effect issue.

# **5.2 Future Work**

The future work of this thesis can focus to improve the performance of the extended control plane on the following aspects.

- The control speed in this SDN control plane is limited to the serial protocol interface which supports up to 5 Mb/s. To reduce the latency, a high speed data collection interface can be investigated.
- More extensions on OF protocol are needed to enhance the control functionalities in the SDN control plane.
- In current design, network resources like network topology is handed by the global controller. For the purpose of eliminating the overload in global controller, the local controller should be able to intelligently manage a portion of the network resources to make fast local actions.

In the cross-layer impairment-aware protection scheme, the controller drops the poor channel and assigns a clean one to maintain the signal quality. However, with the changing of the network conditions, the drop channel may turn out to provide a high signal performance. The future work can investigate a mechanism to recycle the drop channel thus to save the network resources.

In the work of reach-adaptive modulation assignment, the accuracy of the predictive OSNR network model can be improved. Future work can extend the proposed assignment idea to the multichannel networks to investigate and simulate the spectral efficiency of the whole network.

The rapid network resource assignment in the agile optical network may causes network instability such as power excursion and transient problems, thus an in-depth analysis of network stability should be the future work.
## References

[1] Kilper, Daniel, et al. "Optical networks come of age." Optics and Photonics News 25.9 (2014): 50-57.

[2] Alcatel Lucent. White Paper: Agile optical networking: more than moving light

[3] Kilper, Daniel, et al. "Efficient and agile optical networks." *Optical Network Design and Modeling (ONDM), 2013 17th International Conference on*. IEEE, 2013.

[4] Gringeri, Steven, Nabil Bitar, and Tiejun J. Xia. "Extending software defined network principles to include optical transport." *Communications Magazine, IEEE* 51.3 (2013): 32-40.

[5] Tomkos, I., E. Palkopoulou, and M. Angelou. "A survey of recent developments on flexible/elastic optical networking." *Transparent Optical Networks (ICTON), 2012 14th International Conference on*. IEEE, 2012.

[6] Shen, Zhi-shu, et al. "A novel elastic optical path network that utilizes bitrate-specific anchored frequency slot arrangement." *Optics express* 22.3 (2014): 3169-3179.

[7] Gringeri, Steven, et al. "Flexible architectures for optical transport nodes and networks." *Communications Magazine, IEEE* 48.7 (2010): 40-50.

[8] Fu, Yonghong, et al. "A Hybrid Hierarchical Control Plane for Flow-Based Large-Scale Software-Defined Networks." *Network and Service Management, IEEE Transactions on* 12.2 (2015): 117-131.

[9] Tootoonchian, Amin, and Yashar Ganjali. "HyperFlow: A distributed control plane for OpenFlow." *Proceedings of the 2010 internet network management conference on Research on enterprise networking*. 2010.

[10] S. H. Yeganeh and Y. Ganjali, "Kandoo: A framework for efficient and scalable offloading of control applications," in Proc. ACM SIGCOMM HotSDN, 2012, pp. 19–24.

[11] Curtis, Andrew R., et al. "DevoFlow: scaling flow management for high-performance networks." *ACM SIGCOMM Computer Communication Review*. Vol. 41. No. 4. ACM, 2011.

[12] Hassas Yeganeh, Soheil, and Yashar Ganjali. "Kandoo: a framework for efficient and scalable offloading of control applications." *Proceedings of the first workshop on Hot topics in software defined networks*. ACM, 2012.

[13] Koponen, Teemu, et al. "Onix: A Distributed Control Platform for Large-scale Production Networks." *OSDI*. Vol. 10. 2010.

[14] Phemius, Kévin, Mathieu Bouet, and Jérémie Leguay. "Disco: Distributed sdn controllers in a multi-domain environment." *Network Operations and Management Symposium (NOMS), 2014 IEEE*. IEEE, 2014.

[15] https://osrg.github.io/ryu/

[16] S. Das, "Extensions to openflow protocol in support circuit switching, addendum to openflow protocol specification (v1.0)," http://www. openflow.org/wk/index.php/PAC.C, June 2010.

[17] L.L, "OpenFlow Protocol Extension for Agile Optical Network"

[18] Pereira, Helder A., et al. "OSNR model to consider physical layer impairments in transparent optical networks." Photonic Network Communications 18.2 (2009): 137-149.

[19] Chitgarha, Mohammad Reza, et al. "Demonstration of WDM OSNR performance monitoring and operating guidelines for pol-muxed 200-Gbit/s 16-QAM and 100-Gbit/s QPSK data channels." Optical Fiber Communication Conference. Optical Society of America, 2013.

[20] Ahsan, Atiyah, et al. "Autonomous OSNR monitoring and cross-layer control in a mixed bit-rate and modulation format system using pilot tones."Photonic Networks and Devices. Optical Society of America, 2014.

[21] Liu, Lei, et al. "Dynamic OpenFlow-Based Lightpath Restoration in Elastic Optical Networks on the GENI Testbed." Journal of Lightwave Technology33.8 (2015): 1531-1539.

[22] PacketLight Networks. White Paper: ROADM - The Core of Agile Optical Networks, 2009

[23] Perrin, Sterling, et al. White Paper: The Need for Next-Generation ROADM Networks, 2010

[24] Zhou, Xiang et al. "For the Long Haul: Maximizing Transmission Distances for 400-Gb/s Signals over the Existing Grid" <u>http://www.research.att.com/articles/featured\_stories/2013\_05/201305\_Long-Haul.html?fbid=RGe2Zh3XyRD</u>

[25] Kozicki, Bartlomiej, et al. "Distance-adaptive spectrum allocation in elastic optical path network (SLICE) with bit per symbol adjustment." *Optical Fiber Communication Conference*. Optical Society of America, 2010.

[26] Sakamaki, Y., et al. "Filtering penalty reduction by adjusting passband shape in optical filter for 127 Gbit/s DP-QPSK signal transmission." *Electronics Letters* 47.11 (2011): 665-667.

[27] Yang, M., et al. "Traffic-aware non-uniform passband assignment in elastic optical networks." *Photonics Conference (IPC), 2015.* IEEE, 2015.

[28] http://archive.openflow.org/wp/learnmore/

[29] Zhao, Jijun, et al. "Study of Q-factor estimation model based on multi-physical impairments in transparent optical networks." *Journal of Communications* 7.10 (2012): 774-780.

[30] Cvijetic, Milorad, and Ivan Djordjevic. Book: *Advanced optical communication systems and networks*. Artech House, 2013.

[31] Rahman, Atta, et al. "A Real Time Adaptive Resource Allocation Scheme for OFDM Systems Using GRBF-Neural Networks and Fuzzy Rule Base System." *International Arab Journal of Information Technology (IAJIT)* 11.6 (2014).

[32] Sharma, Nitin, and Alagan Anpalagan. "Differential evolution aided adaptive resource allocation in OFDMA systems with proportional rate constraints."*Applied Soft Computing* 34 (2015): 39-50.

[33] Kajioka, Shinsuke, Naoki Wakamiya, and Masayuki Murata. "Autonomous and adaptive resource allocation among multiple nodes and multiple applications in heterogeneous wireless networks." *Journal of Computer and System Sciences* 78.6 (2012): 1673-1685.

[34] Huang, Yurong Grace, Jonathan P. Heritage, and Biswanath Mukherjee. "Connection provisioning with transmission impairment consideration in optical WDM networks with high-speed channels." Journal of lightwave technology 23.3 (2005): 982.

[35] Freude, Wolfgang, et al. "Quality metrics for optical signals: eye diagram, Q-factor, OSNR, EVM and BER." *Transparent Optical Networks (ICTON), 2012 14th International Conference on*. IEEE, 2012.

[36] Agilent Technologies. "Making OSNR Measurements In a Modulated DWDM Signal Environment"

[37] National Instruments. "Introduction to FPGA Technology: Top 5 Benefits"

[38] ONF. https://www.opennetworking.org/sdn-resources/sdn-definition

[39] Shirazipour, Meral, et al. "Realizing packet-optical integration with SDN and OpenFlow 1.1 extensions." *Communications (ICC), 2012 IEEE International Conference on*. IEEE, 2012.

[40] Das, Saurav, Guru Parulkar, and Nick McKeown. "Why OpenFlow/SDN can succeed where GMPLS failed." European Conference and Exhibition on Optical Communication. Optical Society of America, 2012.

[41] Yick, Jennifer, Biswanath Mukherjee, and Dipak Ghosal. "Wireless sensor network survey." Computer networks 52.12 (2008): 2292-2330.

[42] Cisco. Cisco White Paper: The Zettabyte Era: Trends and Analysis, 2014-2019. http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-indexvni/VNI\_Hyperconnectivity\_WP.html

[43] Alcatel Lucent. Alcatel Lucent White Paper: Metro Network Traffic Growth: An Architecture Impact Study. <u>http://www.tmcnet.com/tmc/whitepapers/documents/whitepapers/2013/9378-bell-labs-metro-network-traffic-growth-an-architecture.pdf</u>

[44] Cisco. Cisco White Paper: Cisco Global Cloud Index: Forecast and Methodology, 2014–2019. http://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/Cloud\_Index\_White\_Paper.pdf

[45] Ahsan, Atiyah. Dissertation: Real-time Awareness and Fast Reconfiguration Capabilities for Agile Optical Networks.

[46] Sekiya, Motoyoshi and Olga, Vassilieva. Photonics network and data analytics, DTU Photonic Workshop 2015.

[47] Pavel, Lacra. "OSNR optimization in optical networks: Modeling and distributed algorithms via a central cost approach." Selected Areas in Communications, IEEE Journal on 24.4 (2006): 54-65.