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CHARACTERIZATION AND EXPERIMENTAL VALIDATION OF RECONFIGURABLE OPTICAL ADD/DROP MULTIPLEXERS FOR NEXT GENERATION NETWORK

by

CHOUDHURY ABDULLAH AL SAYEED

A thesis submitted to the Faculty of Graduate and Postdoctoral Studies in partial fulfillment of the requirements for the degree of

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"With the name of God,
The most Gracious, The most Merciful"

To My Parents

ABSTRACT

This thesis proposes a detailed design layout for the next generation optical metropolitan network to be equipped with Reconfigurable Optical Add/Drop Multiplexer (ROADM) subsystems. It demonstrates the key features of ROADM subsystems including the development of ring-to-ring interconnection in optical domain.

Simulation models are developed for the ROADM subsystems that can easily be configured according to the devices' available specification sheet. The developed simulation models have been verified with experimental measurements obtained from a reconfigurable all-optical metro network testbed. Such simulation modules will be valuable in planning and designing the next generation metro optical networks.

Combining the outcome of the research results presented in the thesis, a hybrid reconfigurable add/drop module is proposed. The proposed hybrid architecture can achieve lower loss among the existing 3rd generation ROADM modules. The functionality of ROADMs can also be improved by an Intelligent ROADM subsystem proposed for the next generation dynamically provisioned wavelength network.

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ASE	Amplifier Spontaneous Emission	3.3.2
AWG	Arrayed Waveguide Grating	3.1.1
B&S	Broadcast and Select	2.1
BER	Bit Error Rate	3.4
BERT	Bit Error Rate Tester	3.4
CAPEX	Capital-Expenditure	1
C-band	Conventional Band	3.4.1
CD	Chromatic Dispersion	3.3
CRC	Communications Research Centre	1.6
DCE	Dynamic Channel Equalizer	2.1.2
DCM	Dispersion Compensation Module	2.1
DPON	Dynamically Provisioned Optical Network	6
DSM	DeMux/Switch/Mux	2.1
DWDM	Dense Wavelength Division Multiplexing	1
E>O	Electrical-Optical	3.3.1.6
EDFA	Erbium Doped Fibre Amplifier	1.6
ER	Extinction Ratio	3.3.1
FEC	Forward Error Correction	3.4
GbE	Gigabit Ethernet	1.2
GUI	Graphical User Interface	4.1.1
I2C	Inter-Integrated Circuit	3.1.3
IC	Integrated Chip	3.1.2
IL	Insertion Loss	3.3.1.1
IP	Internet Protocol	1.2
I-ROADM	Intelligent Reconfigurable Optical Add/Drop Multiplexer	1.7
Laser CW	Continuous-Wave Laser	3.3.1.6
MEMS	Micro-Electro Mechanical Systems	1.3
NRZ	Non-Return-to-Zero	4.2.1

O>E	Optical-Electrical	3.3.1.6
OADM	Optical Add/Drop Multiplexer	1.2
OCPM	Optical Channel Performance Monitor	3.4
O-E-O	Optical-Electrical-Optical	1.2
OPEX	Operational Expenditure	1
OSA	Optical Spectrum Analyzer	4.1.1
OSNR	Optical Signal-to-Noise Ratio	1.1
OXC	Optical Cross Connect	1.2
PADM	Packet Add/Drop Multiplexer	2.2
PBC	Polarization Beam Combiner	Appendix B
PBS	Polarization Beam Separator	Appendix B
PDL	Polarization Dependent Loss	3.3.1.1
PIN	Positive-Intrinsic-Negative	Appendix B
PLC	Planar Lightwave Circuit	1.3
PMD	Polarization Mode Dispersion	3.3
PRBS	Pseudo Random Bit Sequence	4.2.1
PXC	Photonic Cross Connect	3.2
R-AON	Reconfigurable All-Optical Network	1
RBW	Resolution Bandwidth	3.4
ROADM	Reconfigurable Optical Add/Drop Multiplexer	1.2
Rx	Receiver	1.3
SDH	Synchronous Digital Hierarchy	1.1
SMF	Single Mode Fibre	1.6
SNR	Signal-to-Noise Ratio	3.4
SONET	Synchronous Optical Network	1.1
Tx	Transmitter	1.3
VOA	Variable Optical Attenuator	2.1
WB	Wavelength Blocker	1.3
WSS	Wavelength Selective Switch	1.3

List of Symbols

		SECTION OF 1ST APPEARANCE
BER	Bit Error Rate	3.4
N	Total number of channels	3.2
λ	Channel wavelength	3.2
$P_{EDFA_{IN}}$	Power at the input of EDFA	3.2
$P_{N_{dBm}}$	Combined power of N number of channels	3.2
$P_{Ch_{mw}}$	Power of each channel in mW	3.2
L	Fibre span	3.2

CHAPTER 1: INTRODUCTION

In today's communication networks, the demand for higher bandwidths at lower costs are increasing enormously. the continued growth of today's internet and broadband communication services pushes the service providers and equipment vendors to look for new technologies that will help them to build a network with enormous capacity and offer the services to the customers at lower costs. optical technologies based on modern artifacts help the service providers to maximize their network capacity with reduced cost of bandwidth. this in turn leads to the growth of new sets of applications that set thriving thrust for more bandwidth. this positive feedback cycle for the demand on bandwidth pushes the service providers to the development of reconfigurable all-optical networks (R-AONs). R-AONs combined with dense wavelength division multiplexing (DWDM) technology can help the service providers to meet the challenge of this surge of traffic demands and also to maximize the utilization of their existing network. R-AONs provide flexibility to the service providers, especially on the dynamic provisioning of their wavelengths that ultimately reduce the capital- (CAPEX) and operational-expenditure (OPEX) of the overall network. the evolution of this reconfigurable optical networks and their appliances are briefly described in the following section.

1.1. Evolution Of Optical Networks

Optical fibre transmission has given the service providers a great relief in meeting the increasing bandwidth demand of the telecommunication networks. In the late '90s, many telecom operators upgraded their services by laying out optical fibres all over their networks [RaSi02]. In the early stage of optical networks, fibres were used simply as a replacement for copper cable and handling of data had been remained in the electronic domain. Synchronous

Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) are among those first generation of optical networks. In such networks, the electronics at the node must have to handle all the data intended for that node and also the data that is being passed through the node towards the other nodes in the network. As the transmission speeds in the network are increasing to meet the demand for high bandwidth applications, it becomes more and more difficult to perform all the switching and processing functions electronically [RaSi02]. If the data, which is not intended for that node could be routed in the optical domain, the burden on the underlying electronics within the node would eventually be reduced.

Maintaining the transparency of the signal all its way from source to destination is become another significant factor. As the signal travels in optical form, its Optical Signal-to-Noise Ratio (OSNR) reduces due to the transmission impairments such as dispersion and other non-linear effects in the fibre. Thus the signal needs to be regenerated that involves converting the signal from optical to electrical form and after retiming with reshaping, converting the electrical signal back into the optical form. These expensive electronic regenerators in the path of the optical signal obviously reduce the transparency of the signal [RaSi02] and increase the overall cost. All these key factors drive the service providers to build All-Optical Networks (AONs) that can help them to provide transparent wavelength services to the customers. AON brings the optical networks to their second generation that involves switching and routing functions – all in optical domain. As the range of the optical networks are expanding and the technologies associated with AON are maturing, operators are trying to add more flexibility on the provisioning and management of their wavelengths. Reconfigurable AONs can help the service providers to reduce their management and operation costs by providing automatic, fast provisioning and dynamic end-to-end connections where the network setup and release is based on traffic demand [WaSh02]. R-AONs also help in network planning and capacity forecasts and can enhance the network survivability by fault recovery in the optical layer.

1.2. Need for ROADM in Today's Network

The re-configurability of All-Optical Networks relies on the integration of Reconfigurable Optical Add/Drop Multiplexers (ROADMs) into our present optical network with DWDM technology. ROADMs can be defined as optical modules capable of adding/dropping or passing through (express) any or all wavelengths present in the DWDM signal with remote management capability. Because of the increasing demand for applications like audio and video streaming and broadband services, the metro core backbone is becoming more diverse geographically than it was ever before. Thus, service providers are migrating more quickly to the DWDM technology that offers them ample bandwidth, and protocol independence giving the companies the ability to transport virtually any kind of traffic and maximize their revenues.

The presently deployed metro WDM networks are mainly using fixed Optical Add/Drop Multiplexers (OADMs) in which the number of wavelengths in the network and their service patterns are fixed and predetermined. This imposes a big limitation to the service providers on the management of their optical networks, especially on the handling of churn. Truck-rolls are always required to send in the field to re-assign the optical paths and to launch a new wavelength, new equipments have to be installed that increase both CAPEX and OPEX for the optical network. Thus, it is very important for the service providers to attain flexibility on the handling of churn and the growth of their optical network and also to achieve complete control over every part of their network. Monitoring optical power, performance, and providing automatic gain equalization for every channel are other important factors for which service providers are concerned about. It is also challenging to the vendors to install devices in the network that provide protocol independence i.e., support voice, video and data over Gigabit Ethernet (GbE), Internet Protocol (IP), or SONET so that carriers do not have to consider any more about different standards among service providers for provisioning. The devices in the network should support optical transmission and routing without any sorts of signal conditioning and can easily be integrated into the present point-to-point and ring topologies and will also lead to the evolution of more efficient mesh network topologies.

All these goals can be achieved by integrating the service of ROADM subsystems into the present DWDM network. ROADM offers flexibility on the provisioning of wavelengths regardless of how the network changes. It effectively alleviates the need for service provisioning when new services are added to the network and offers flexibility to the service providers on the handling of churns. In order to achieve reconfigurability on wavelengths, ROADMs can be deployed in long-haul, metro core, or in access networks. Service providers would be able to control any set of wavelengths to be added/dropped, or forwarded to any part of these networks. One of the best features occurs with ROADMs is the reconfigurable transparent ring-to-ring interconnections that is going to alleviate the use of costly Optical-Electrical-Optical (O-E-O) regenerators and Optical Cross Connects (OXCs) within the network. ROADM also helps in schemes such as gain equalization and dispersion compensation techniques. Almost all the ROADM devices appear with east-west separability that provide 1+1 protection and bi-directional traffic flow thus, supporting the present

SONET/SDH networks. ROADMs will be the key element for the future metro network in order to have high bandwidth management capability and reduced capital- and operational-expenditure.

As the traffic demands are increasing, lots of service providers are introducing ROADMs into their network. Analysts firms are predicting huge increases in ROADM revenue and their rapid deployments within the next few years. In the year of 2004, more than $100 US million worth of ROADM equipment was sold to the long-haul and commercial metro vendors and it was expected to be doubled by the year 2005 [Full05].

1.3. Current Research Activities

In order to add more flexibility to the network, network developers were spending a lot of effort on the development and improvement of ROADM architectures from early on. Initially, the 1st generation of reconfigurable OADMs was demonstrated [VeRi98] with OXCs and O-E-O regenerators, and their integration were showed for future optical networks. Later ROADMs came up with optical circulators [TrZh01], while some researchers [JiZh01, YiAi02, WaSh02, TzZa03] presented DeMux/Switch/Mux (DSM)-based architectures for ROADM modules. However, these 1st generation ROADM architectures were suffering from two major factors: (1) large CAPEX/OPEX, and (2) high insertion losses because of the lacking of integration among different internal modules.

In order to cut down the CAPEX/OPEX that is the major cost of the system, network developers developed integrated ROADM subsystems. Instead of using separate Mux/DeMux and switch modules, compact Wavelength Blocker (WB)-based architectures [LiLi02, RhTo02, ToVa02, RhTo03, HeWa04] have been developed, while a few field demonstrations [BoSh02, SoCh03] of these modules have been reported in terms of loss, crosstalk and cascadability. These WB-based designs brought the ROADM subsystems to their 2nd generation providing more flexibility to the service providers, especially on the dropping of selective wavelengths and then broadcasting new channels [Para05, Keyw05]. However, these 2nd generation ROADM modules suffered from two problems: (1) the insertion losses still remained high although the cost was significantly reduced; (2) the design is totally unsuitable for interconnection with other ROADM modules (i.e. for higher degree expansion) as each interconnection requires the installation of additional WB modules that ultimately increases the CAPEX and OPEX for the overall network.

Hence to overcome these problems, some of the researchers [ZhMu05, HeWa04] introduced tunable filters with ROADMs, while couple others [ViBa04, Keyw05] presented simplified ROADM designs without wavelength blockers using Planar Lightwave Circuit (PLC) technology [WaSh02]. These simplified ROADM designs offers flexibility on higher degree expansion bringing the ROADM into its 3rd generation. However, the tunable ROADMs are not so popular yet because of the high price of tunable Transmitters (Txs)/Receivers (Rxs), while in PLC-based designs each port remains channel specific. Hence, in order to add the flexibility of colorless ports to the ROADM subsystems, Wavelength Selective Switch (WSS)-based architectures [EaCa03, Toml04, BoJo04, Keyw05] have been introduced that ultimately reduces the total number of ports in the network. Note that a patent [DyWa05] is recently published without revealing any further information on WSS module capable of doing both add and drop functions.

Since the technology of ROADM is relatively new to the market, service providers are really confused about the level of reconfigurability they would be able to achieve by installing ROADMs into the present network. Some researchers [Keyw05, BoSh02] have identified different ROADM applications, while some others [GuZh05, BoSh02, ToVa02, JiZh01, VeRi98] showed the next generation network architecture with ROADMs without revealing much details. The traditional 1+1 protection schemes with ROADMs have been demonstrated by [RhTo03, JiZh01], while some others [SuZh05, AnBo02, VeRi98] tried to establish interconnection with other ring networks with the help of OXCs and O-E-O regenerators in conjunction with ROADMs. Several test beds were reported by [BoSh02, LiLi02, WaSh02, RhTo03, SoCh03] to characterize the performance of different ROADM architectures. However, their tests were performed either on 1st or 2nd generation of ROADM architectures and were applicable only for low-channel-count applications.

Couple commercial vendors e.g. DuPont Photonics [DuPo05], JDS Uniphase [JPLC06, JWSS06], Metconnex Inc. [Metc05a, Metc05b, WsMe05] have recently introduced the most advanced 3rd generation ROADM modules. These 3rd generation structures can easily be upgraded to higher degree applications and can be constructed using PLC [Full04, JPLC06, DuPo05], Micro-Electro-Mechanical Systems (MEMS) technology [Ligh05], or a combination of both e.g. [JWSS06, Metc05a, Metc05b, WsMe05]. However, these highly advanced structures are also suffering from high insertion losses for which vendors usually recommend to install amplifiers with the ROADM module that, in turn, increases their initial deployment cost.

1.4. Motivations

The deployment of these 3rd generation ROADM modules is going to bring a radical change in the architecture for next generation metro network. However, according to my best knowledge, no test result or network design has yet been published on these latest ROADM modules. Many service providers are soon going to deploy ROADMs of higher channel capacities into their network and it is highly important for them to know the characteristics of these ROADM modules in metro network environment in terms of network design, amplifier placement, associated fibre segments, and module's cascadability.

Unfortunately, providers in today's metro optical network are using ROADMs only for fibre-relief type applications [WaSh02]. Optical-Electrical-Optical (O-E-O) regenerators and Optical Cross Connects (OXCs) are still being used [SuZh05, AnBo02, VeRi98], in the network for interconnection between different ring networks. However, with the increase in traffic demands and transmission speeds, these O-E-O conversions become inefficient in terms of transparency and latency. This scenario can only be improved by moving these interconnection features into optical domain that will alleviate the use of these costly O-E-O regenerators from the network. ROADMs can be used to setup transparent interconnections among different ring networks that will certainly add more flexible control and reconfigurability to the whole network.

Although the 3rd generation of ROADM arrives with higher flexibility to the service providers on the provisioning of wavelengths, the challenge still remains on developing a low-loss and low-cost architecture for ROADM devices that will support high channel count applications at high transmission speeds. In conjunction, the control interface for ROADM modules are required to be upgraded so that the ROADM module can dynamically provision wavelengths according to the customer needs.

One of the key research areas on ROADM architectures is to improve their switching speeds. The current switching speeds for ROADM's MEMS [JPLC06], or thermo-optic switches [DuPo05] are only around 3 ms to 5 ms. The present optical network is slowly diverting to its next generation photonic packet switching network [FuWa06] that requires high speed switching (in the order of ns to μs). Even though the latest available ROADM technologies are not yet ready for that, our testbed design has allowed for this possibility.

Finally, the deployment and testing of ROADM and other optical equipments are still very expensive. Hence, it would be highly helpful to the service providers if simulation models can be developed for these expensive optical modules that could predict their true behavior in different network environments. With the help of proper simulation models, service providers would be able to design and optimize their network parameters well in advance without buying these expensive components.

1.5. Objectives

In order to meet the above mentioned challenges, the objectives of this thesis are to:

1) Develop detailed design schemes for the next generation reconfigurable metro network equipped with ROADMs.
2) Develop accurate simulation models for the reconfigurable equipments that can be effectively used in design of future network.
3) Characterize the performance of the most advanced 3rd generation ROADM modules in metro network environment, and also experimentally validate the developed design schemes and simulation modules.
4) Improve the design and the control of ROADM subsystems in terms of loss, cost and switching speeds.

In the long run, I would like to propose a new architecture for ROADM subsystems with improved functionality and explore their new applications for the next generation network.

1.6. Methodologies

Among the several available ROADM technologies, this thesis concentrates mainly on the application of the most advanced PLC-based ROADM modules in metro core networks. PLC-ROADMs have recently become popular because of their simpler manufacturing process. In order to integrate the service of ROADMs into the next generation network, the thesis concentrates on obtaining detailed design schemes in terms of the maximum length of the associated fibre segments, or the characteristics and the placement of the optical amplifiers. The emphasis is on developing mathematical formulations based on the characteristics of the ROADM and its associated optical equipments in conjunction with traffic demands so that they can be used to identify design parameters for complex network architectures.

In order to provide more convenience to the service providers, the major part of this thesis also deals on developing simulation models for expensive optical equipments. Models are developed for the PLC-ROADM module and couple other associated optical components. VPI Transmission Maker (WDM) [VPIP06] is specifically chosen for this task because of its suitability in designing and optimizing the physical layers in our networks, and also because of their valuable technical supports.

A reconfigurable all-optical metro network testbed will then be designed and implemented that verifies the developed simulation models. The testbed consists of a prototype 16-channel PLC-ROADM module that will also serve the purpose of characterizing the performance of this most advanced ROADM module into next generation metro optical network. Single Mode Fibre (SMF) spans with Erbium Doped Fibre Amplifiers (EDFAs) are used to setup the testbed because they are available at Communications Research Centre (CRC)'s optical networking lab. Measurements are performed in order to obtain design parameters e.g. associated fibre span and the cascadability of the ROADM module, or the placement of optical amplifiers in the network. The thesis concentrates on designing new architectures for next generation networks irrespective of the fibres and amplifiers which are already deployed in the field. Simulations models will also be developed for the complete AON testbed so that results obtained from the simulations can be compared with the experimental results for model verification.

Once the simulation models are verified, the thesis will concentrate on developing next generation architectures with ROADMs. The verified simulation models can then be used to develop new architecture for ROADM subsystem that could reduce the insertion losses within ROADM modules and also help on reducing the operational expenditure for the overall network.

Finally, to improve the functionality of ROADM modules and also to make them ready for the next generation Dynamically Provisioned Optical Network (DPON), the thesis would like to concentrate on improving the control of these 3rd generation ROADM modules, thus developing an Intelligent ROADM (I-ROADM) subsystem. Such I-ROADM would be able to dynamically balance the optical power levels and will help the service providers to dynamically reconfigure the lightpaths over the network according to the customer demands.

1.7. Contributions

The following are the contributions of this thesis:

1) Network integration and simulation:

i) Detailed design schemes have been presented to integrate ROADMs into next generation network. One of the most important facts revealed out of this design layout is that the conventional idea of equipping each ROADM device with amplifiers is not a necessity unless there is only one channel to transmit in the network.

ii) Simulation models have been developed for the expensive reconfigurable optical equipments that can predict the behavior of real modules as well as overall system performance with an acceptable accuracy. The developed simulation models will definitely help the R&D community and network engineers in planning and designing their next generation metro optical network without buying these expensive components.

2) Characterization and experimental validation:

i) The performance of one of the most advanced 16-channel PLC-ROADM is characterized for next generation metro network environment.

ii) This experimental characterization also validates the proposed network designs and simulation models.

3) New architectures:

i) A hybrid design for ROADM subsystem is proposed in this thesis that can attain a lower loss for express-channels and sets up a much better balance in terms of cost and operational flexibility as compared to the existing 3rd generation ROADM modules.

ii) Detailed design lay-outs are proposed for interconnections among different ring networks in optical domain realized by using PLC-based ROADMs. To the best of my knowledge, this is the first attempt to promote reconfigurable transparent ring-to-ring interconnection that is going to alleviate costly O-E-O regenerators and OXCs.

iii) Intelligent ROADM (I-ROADM) subsystem is proposed that will make the ROADM ready to face the challenge for the next generation network.

1.8. Thesis Organization

This thesis covers almost all the aspects of a ROADM module – starting from its evolution in architectures to its detailed characterization and integration to the next generation metro network environment. After the Introduction of Chapter 1, Chapter 2 describes the evolution of ROADM. Chapter 3 concentrates on the architecture and integration of PLC-based ROADMs into next generation network and describes the development of simulation models in detail. Chapter 4 demonstrates the metro network test-beds designed and developed to validate experimentally the simulation models and the proposed network architecture. Chapter 5 contributes to the development of next generation architecture with ROADMs. Finally, Chapter 6 concludes the thesis followed by the recommendation for future works for implementing a Dynamically Provisioned Optical Network (DPON) presented in Chapter 7. At the end of the thesis, there are a few appendices. Appendix A discusses the PLC-based ROADM supplied by DuPont Photonics

[DuPo06], while Appendix B describes the development of simulation models for different optical equipments using VPI simulation tool [VPIP06].

1.9. Refereed Publications

Journals:

[1] A. Vukovic, C. A. Al Sayeed, M. Savoie, and H. Hua, "Reconfigurable Optical Network Testbed – Key Enabler in R&D of Dynamically Provisioned Next Generation Solutions," *Photons Journal,* Spring 2006, pp. 19-20, Available: http://www.cipi.ulaval.ca/publications/photons_technical_review/ .

Conference Papers:

[1] C. A. Al Sayeed, A. Vukovic, O. W.W. Yang, and H. Hua, "Hybrid Low Loss Architecture for Reconfigurable Optical Add/Drop Multiplexer," accepted for publication at the *Proc. of IEEE GLOBECOM 2006,* San Francisco, CA, Nov 2006.

[2] C. A. Al Sayeed, A. Vukovic, and O. W.W. Yang, "Performance Optimization of PLC-based ROADM Subsystem in Ring-to-Ring Interconnection", *Proc. of IEEE International Conference on Communications (ICC'06),* Istanbul, Turkey, June 11-15, 2006.

[3] C. A. Al Sayeed, A. Vukovic, O. W.W. Yang, H. Hua, and T. Nguyen, "The Integration of ROADMs into Next Generation Metro Optical Network" *Proc. Photonics North 2006, SPIE*, Québec, Canada, June 5-8, 2006.

[4] C. A. Al Sayeed, A. Vukovic, and O. W.W. Yang, "Transparent Ring-to-Ring Interconnection for Metro Core Optical Network," *Proc. of IEEE/ACM Conference on Communication Networks and Services Research (CNSR 2006),* Moncton, N.B., Canada, May 24-25, 2006, pp. 19-25. ** Received *Best Student Paper Award.*

[5] C. A. Al Sayeed, A. Vukovic, O. W.W. Yang, and H. Hua, "Introducing Intelligent ROADM Subsystems for Dynamically Provisioned Optical Network," *Proceedings of International Workshop on Application Controlled Optical Network (ACON2006),* Ottawa, Canada, May 11, 2006.

Presentations:

[1] C. A. Al Sayeed, "Low Loss Reconfigurable Add/Drop Module for Next Generation's Network," *IEEE-LEOS/OPRA/OPC Workshop on Recent Advancements in Optical Communications*, National Research Council (NRC), Ottawa, Canada, April 25, 2006.

[2] A. Vukovic, C. A. Al Sayeed, "Real-time Wavelength Monitoring in Reconfigurable WDM Networks," *IEEE-LEOS/OPRA/CRC/OPC Workshop on Recent Advancement of Photonics*, National Research Council (NRC), Ottawa, Canada, October 11, 2005.

CHAPTER 2: EVOLUTION OF ROADMs

This chapter concentrates on the evolution of Reconfigurable Optical Add/Drop Multiplexers (ROADMs) in terms of design and architectures. Developers have been paying attention for quite a long period of time to integrate more and more functionalities into the ROADM device that brings ROADM into its 3rd generation of architectures. A detailed view on the development of ROADM architectures is presented in the following sections.

2.1. ROADM Architectures

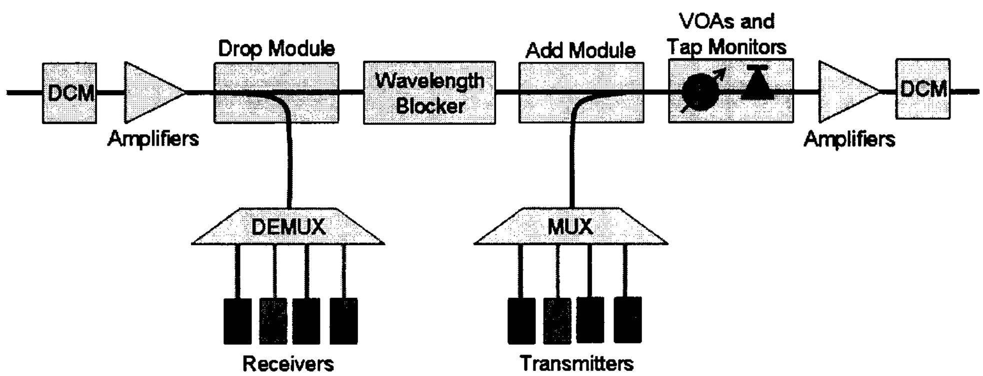


Fig. 2.1. A generic block diagram of a ROADM module

A generic block diagram of a ROADM module is presented in Fig. 2.1. It contains a drop module for dropping any specific channel followed by a Wavelength Blocker (WB) and add module to add any external wavelength in the middle of the transmission. Variable Optical Attenuators (VOAs) and tap monitors are embedded within the device in order to provide remote power adjustment capability for each channel. The node may be accompanied with two amplifiers for the purpose of pre- and post-optical amplification respectively depending on the associated fibre length and losses within the module. The module can also be equipped with Dispersion Compensation Modules (DCMs) to provide equalization schemes for pre- and post-amplifiers that is supposed to be useful for high speed transmission networks (10 Gbps, or 40 Gbps). ROADMs usually come with east-west separability that support the 1+1 restoration infrastructure of the present network. Thus, a compact ROADM subsystem will eliminate the use of other accessories within the node and add more simplicity and reconfigurability to the network.

Several ROADM architectures have been proposed so far by [BoSh02, WaSh02, LiLi02, DuPo05, Metc05b]. Each of them differs based on initial deployment cost, operational flexibility, and capability for future expansion. Optical penalties such as insertion loss, dispersion, and fault characterization capability also play important role in developing different architectures for ROADM. Based on the evolution of ROADM technology, the ROADM architectures have been classified into three broad categories:

1) DeMux/Switch/Mux (DSM)-based architecture
2) Broadcast and Select (B&S)-based architecture and
3) Wavelength Selective Switch (WSS)-based architecture.

Brief descriptions of each of these modules are given in the next few sub-sections.

2.1.1. Demux/Switch/Mux (DSM)-based Architecture

DSM-based ROADM [TzZa03, YiAi02, WaSh02, JiZh01] is one of the 1st generation of ROADM architectures that contain a demultiplexer, a switching element and a multiplexer. The switching element can be an M x N optical switch where M is the number of wavelengths and the N is the number of Add/Drop ports, or it can be a combination of several 2 x 2 optical switches [Metc05a]. In the basic DSM-based ROADM, the full DWDM spectrum is demultiplexed, switched and then re-multiplexed as monolithic block of wavelengths [BaOp03].

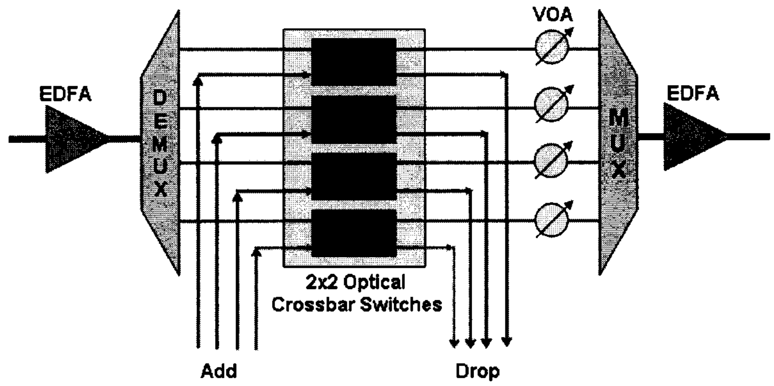


Fig. 2.2. Basic DSM-ROADM architecture based on 2x2 optical switches

Fig. 2.2 shows a basic DSM architecture based on 2x2 optical switches that perform the switching operation of adding, or dropping any particular channel. When an external channel is added, the corresponding switch acts in cross-state to pass the add channel to the output and also to drop the original input wavelength. VOAs can be installed on each wavelength channel for power adjustment purposes, while Erbium Doped Fibre Amplifiers (EDFAs) can be placed for the purpose of pre- and post-amplification.

Although the architecture for DSM-based ROADMs are the simplest and almost ideal for ROADM designs, the lack of integration among these discrete optical components have appeared to be the major drawback of this structure. Each of these individual optical components is very expensive and connecting them with external fibres and connectors increase both the CAPEX and OPEX further for the overall subsystem even before lighting the first service. This huge initial expense has mainly prevented service providers not to deploy DSM-based ROADMs into their network although it was the first successful step to achieve flexibility on the handling of wavelengths. The other limitations of this structure are the high insertion losses and dispersions imposed by the external fibres that make them almost obsolete at the present high speed networks (10 Gbps, or more).

2.1.2. Broadcast and Select (B&S)-based architecture

In order to reduce the initial deployment cost for ROADMs, researches have tried to integrate the discrete components of the DSM architecture that led to the development of the compact Wavelength Blocker (WB)-based architectures [RhTo02, ToVa02, RhTo03, HeWa04] as shown in Fig. 2.3. The WB first demultiplexes the received wavelengths and then can selectively block, or attenuate any number of wavelengths within the spectrum [Ligh05].

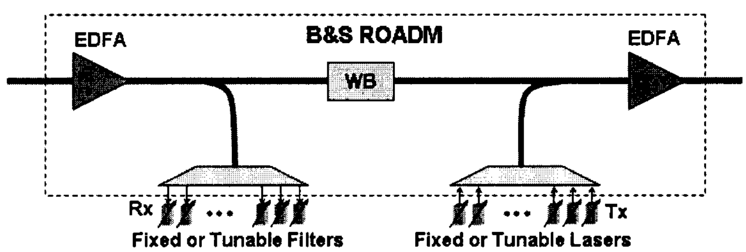


Fig. 2.3. Broadcast and Select (B&S)-based ROADM architecture

These WB-based designs, also known as Broadcast and Select (B&S) architecture, have brought the ROADM subsystems to their 2nd generation providing more flexibility to the service providers, especially on the dropping of selective wavelengths and then broadcasting new channels [Para05, Keyw05]. These WB modules can be manufactured using MEMS technology that can also act as Dynamic Channel Equalizers (DCEs) [Ligh05, LiLi02]. As depicted in Fig. 2.3, the incoming wavelength energies are initially divided between the express and the drop paths. On the drop side, wavelengths can be selected for dropping by using tunable filters, or fixed filters. The core of the architecture contains the WB that selectively blocks the specified *drop* wavelengths and finally at the add module, new wavelengths can be added with the express ones to complete the ROADM. This kind of ROADM is usually known as Degree 2 ROADM. The structure also comes with east-west separability so that no single failure, or repair action can interrupt the traffic movement in more than one direction.

Although the B&S architecture has significantly reduced the initial manufacturing cost the insertion losses especially for express-channels still remains very high. However, the major shortcoming of this architecture has arrived when the module is required to be upgraded into higher degrees (i.e. establishing interconnection with other ROADM modules). Such higher degree expansion requires the installation of additional WB modules with splitters/combiners that ultimately increases the CAPEX/OPEX for the overall network.

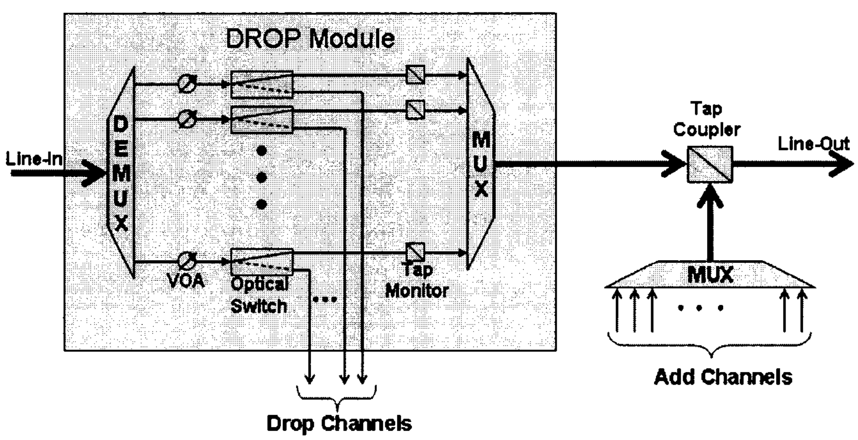


Fig. 2.4. Reconfigurable drop module with multiplexer for add channels [Full04]

To overcome the problems of the B&S structure, especially in upgrading to higher degrees and also to cut down the overall costs, researchers and some commercial vendors [ViBa04, DuPo05, JPLC06] have tried to simplify the model for ROADM modules and have brought the ROADM architectures into its 3rd generation. Instead of introducing one add and one drop module (as shown in Figs. 2.1, and 2.3), they have proposed [Full04] to use either a reconfigurable drop module with monitored multiplexer for add channels (see Fig. 2.4), or a reconfigurable add module with monitored demultiplexer for drop channels (see Fig. 2.5).

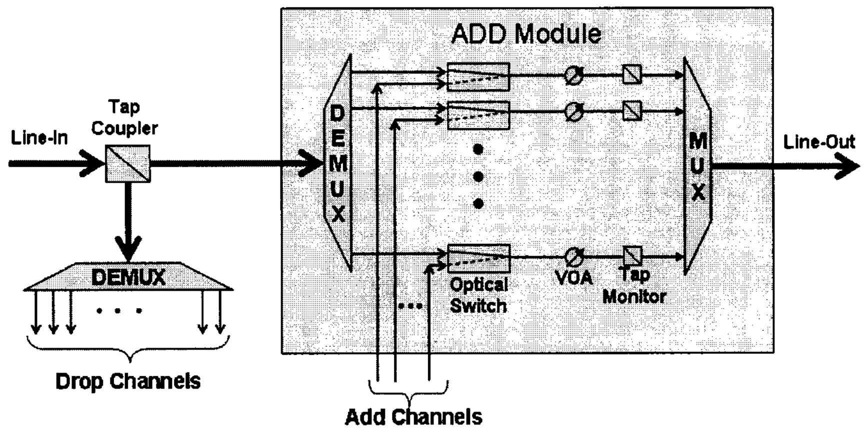


Fig. 2.5. Reconfigurable add module with demultiplexer for drop channels [JPLC06]

This 3rd generation of ROADM architectures can be manufactured using Planar Lightwave Circuit (PLC) technology that enables them to be produced in high volume, thus ultimately reducing the overall costs. The structures can also be upgraded to higher degree applications, i.e. interconnections with other ROADM modules without installing any additional components. However, the major shortcoming of these PLC-based designs are their channel specific ports that, in turn, increases the total number of ports in the network and hence the overall expenditure. The detailed functionality of this 3rd generation PLC-based ROADMs will be discussed in Chapter 3.

2.1.3. Wavelength Selective Switch (WSS)-based Architecture

In order to offer the flexibility of colorless ports to the ROADM subsystems, some developers [Toml04, BoJo04, Metc05b, Keyw05] have introduced Wavelength Selective

Switches (WSSs) as depicted in Fig. 2.7.

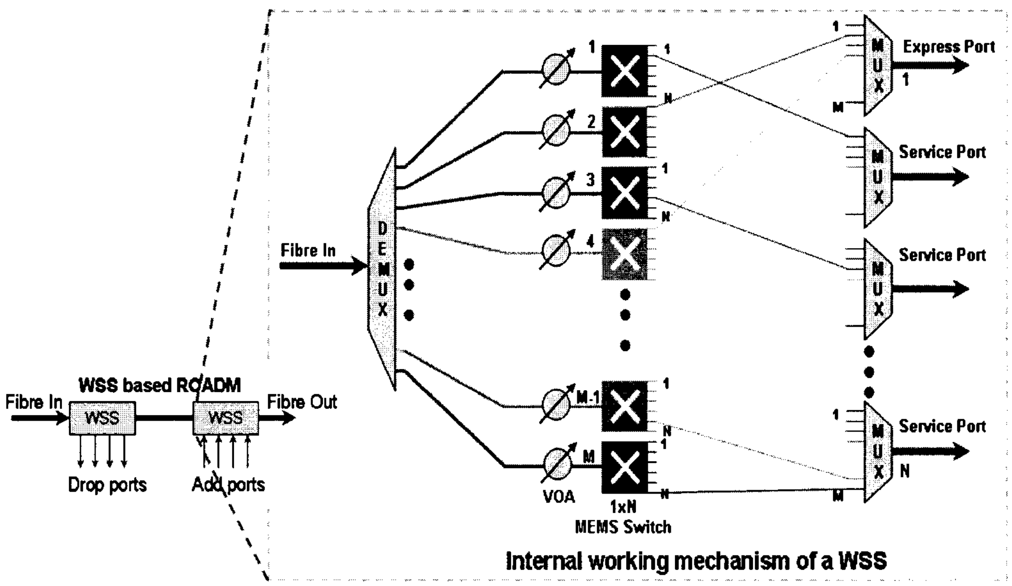


Fig. 2.7. The internal mechanism of a WSS-based ROADM

The WSS module can divert any wavelength from its common input port to anyone of its multiple output ports through the embedded *1xN* optical switches. The introduction of colorless ports in WSS module reduces the total number of ports in the network. The optical path of each module is always reversible so that wavelengths can be either dropped, or added at the service ports. A colorless ROADM subsystem can be built by using WSSs for both of the add and the drop functions [Metc05b] as shown in Fig. 2.7. The first WSS selectively drops wavelengths to any of the drop ports while switching the remaining wavelengths to the express port. The second WSS adds external wavelengths while providing per wavelength attenuation for both add- and express-channels.

The manufacturing of WSS combines the best features of free-space MEMS and PLC technology [JWSS06, Metc05b] although it is possible to be manufactured using solely PLC technology [EaCa03]. In a hybrid WSS module, AWGs (used for multiplexing and demultiplexing operation) and VOAs (for per wavelength or per port attenuation) are manufactured using the integrated PLC technology while the MEMS provides the *any-to-any* switching capability.

Due to the advantage of having colorless ports, WSS offers more flexibility to the service providers than the B&S ROADMs, especially on the handling of wavelengths and also on higher degree expansions. However, the device integrates more optical components than its PLC-counterpart [JPLC06, DuPo05] that makes it more costly than any other existing 3rd generation ROADM modules. The colorless ROADM subsystem also combines two WSS modules [JWSS06, Metc05b] that slightly increases the insertion loss for express-channels and also makes the ROADM control more complex as compared to the PLC-based colored ROADM subsystems. However, for the rest of this thesis, only commercially available WSS modules [JWSS06, Metc05b] will be considered for further reference and comparison.

2.2. ROADM's Evolution in Future

The evolution of ROADMs in terms of architectures and functionality has been described in this chapter. The basic purpose of ROADM is to add and drop wavelengths with remote adjustment capability. Both the researchers and the manufacturing vendors have tried to resolve this issue by improvising new architectures and designs with improved functionality and better management capability. However, the challenge still remains to resolve issues e.g. developing low-loss and low-cost architecture for ROADMs and improving the switching speeds so that ROADM could become ready for the next generation packet switching networks.

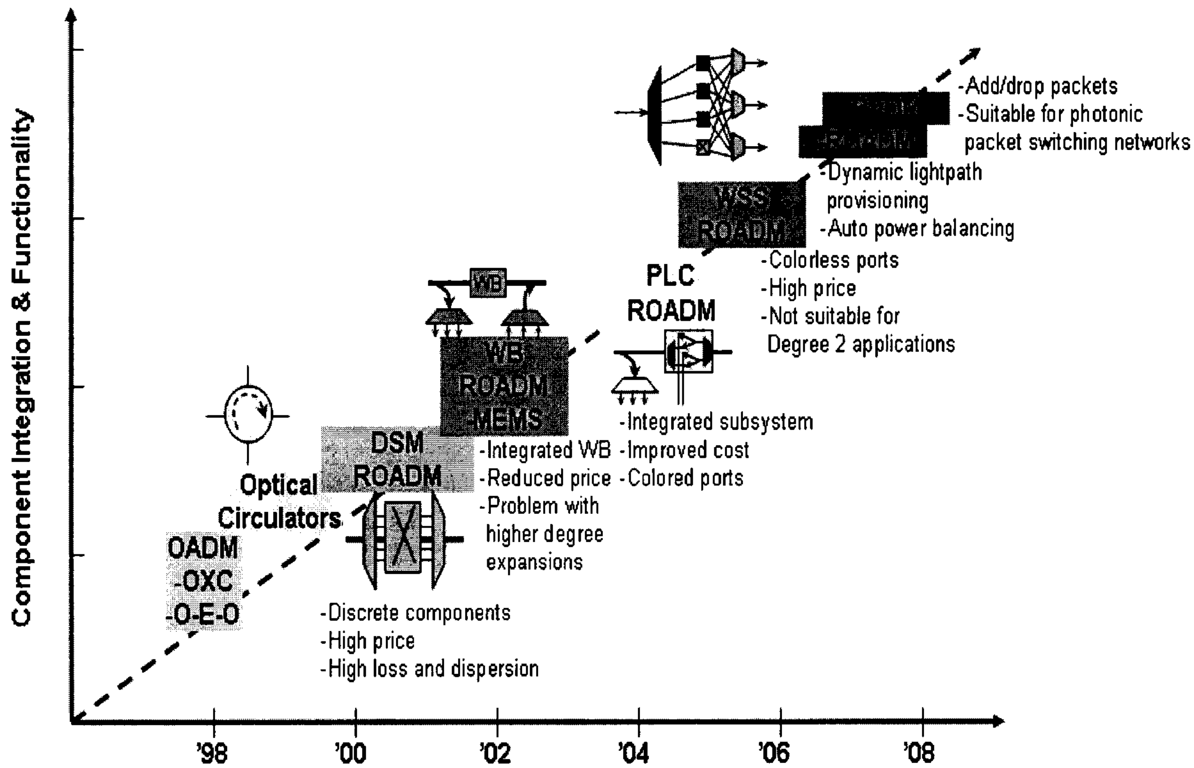


Fig. 2.8. Evolution of ROADM architectures

Fig. 2.8 shows the evolution of ROADM architectures in terms of integration and functionality over the last half of the decade. Researchers are now paying attention to develop Intelligent ROADM (I-ROADM) subsystems that would be able to reconfigure lightpaths dynamically, and Packet Add/Drop Multiplexers (PADMs) to add/drop photonic packets selectively for the next generation metro photonic networks.

ROADMs with different designs and manufactured with different technologies are soon going to be available in the market. Next generation optical network is going to be occupied with ROADMs – a glimpse of which is presented in Fig. 2.9. Based on the ROADMs' functionalities, the latest DCE-based B&S architecture would be suitable only for *Degree 2*[*]

[*] Normal add/drop and express functionalities. No interconnection with other ROADM modules.

applications, while both PLC- and WSS-based ROADMs can be used for higher degree of interconnections (*Degree 3*[†] & *4*[‡]). However, due to the high cost of the present WSS-based colorless ROADMs, they may not be a cost-effective solution only for Degree 2 applications. Service providers should look for their own requirements e.g. maximum planned capacity, channel bandwidth requirements, wavelength granularity and the type of their network before going to deploy ROADMs into their network.

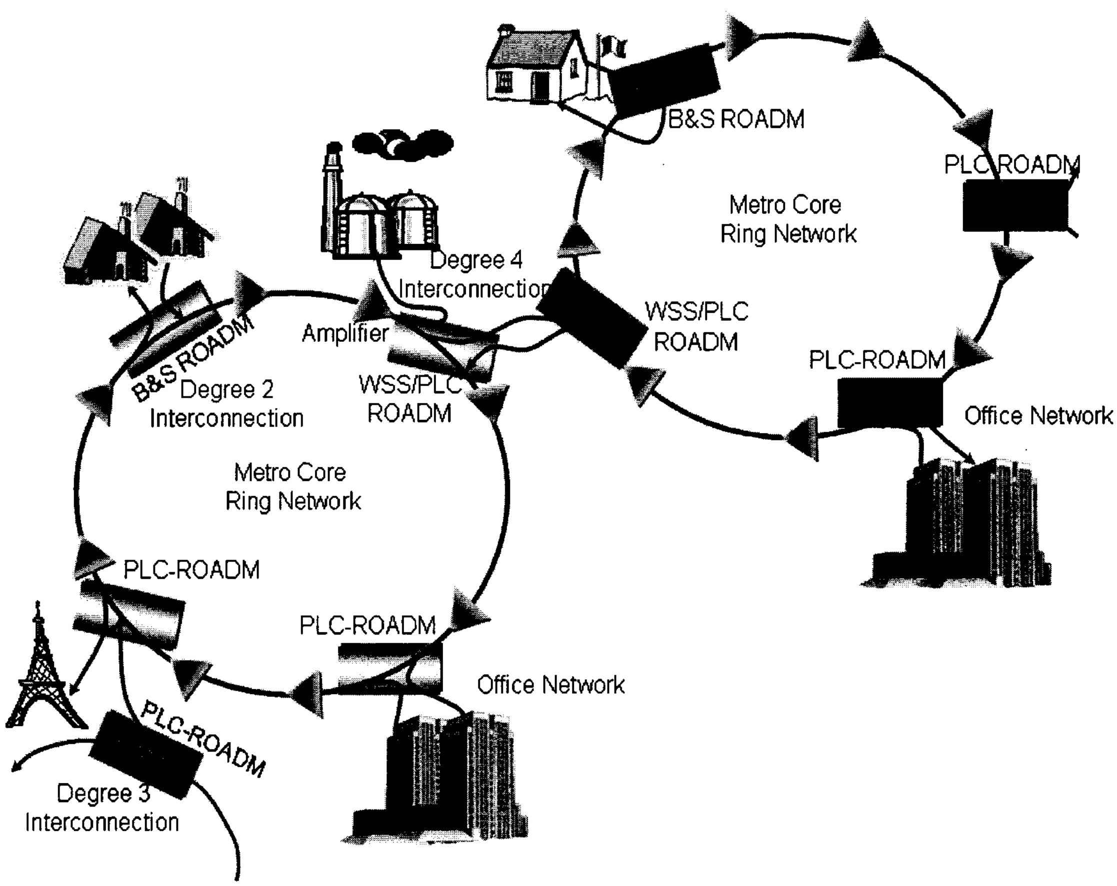


Fig. 2.9. Example of next generation networks with ROADMs

[†] Interconnection with other ROADMs through either add or drop ports (see Fig. 2.9).

[‡] Interconnection with other ROADMs through both add and drop ports (see Fig. 2.9).

CHAPTER 3: SYSTEM OPERATION, MODELING AND ASSUMPTIONS

This chapter mainly concentrates on development of the physical model of ROADM followed by its simulation model. Operations of PLC-based ROADMs with proposed improvements in their functionalities, and their integration into next generation network are presented in detail in this chapter. Development of simulation models, especially for the PLC-ROADM module and other components in the proposed AON system is described in detail in Section 3.2. All the models are developed using *VPI Transmission Maker* simulation tool [VPIP06].

3.1. Operation of A PLC-based ROADM

3.1.1. Internal Structure

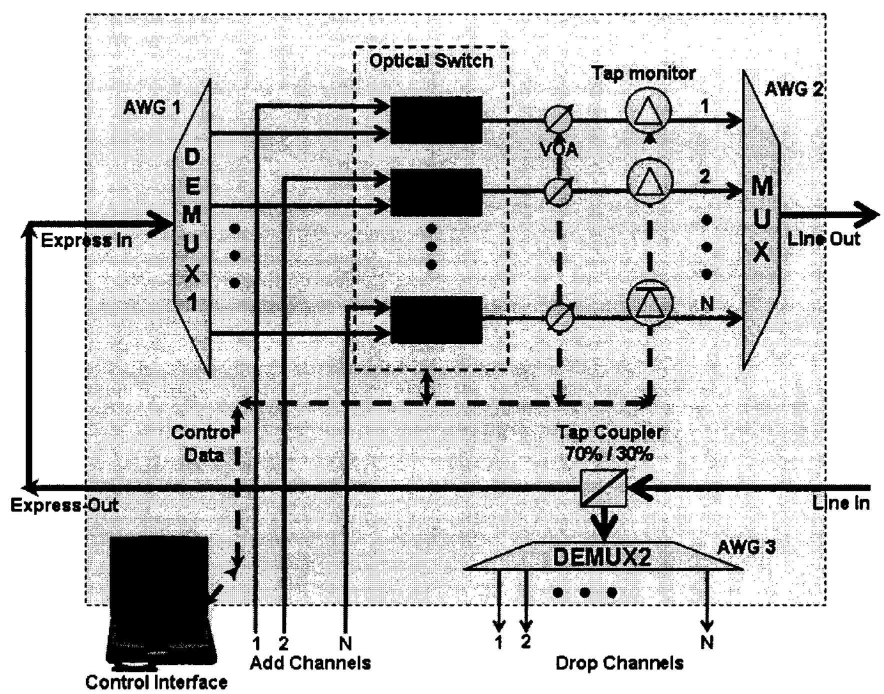


Fig. 3.1. Internal structure of a PLC-based ROADM

Fig. 3.1 shows the internal structure of a typical *N*-channel PLC-based ROADM with a monitored demultiplexer for drop channels followed by a reconfigurable add module. PLC-based ROADMs are generally constructed on waveguide materials based on SiO_2 over Si

(Silicon), or polymer materials [DuPo05, Full04, WaSh02]. The functional technologies of the PLC-based ROADM depend on Arrayed Waveguide Gratings (AWGs), thermo-optic switches, Variable Optical Attenuators (VOAs) and tap monitors that are used for monitoring power in specific channels. Each optical switch acts as a *2*x*1* switch for each channel that can select either the express-channel, or the add-channel for the output. The input wavelengths are usually brought to the *Line-In* input port. A fraction of the input is diverted towards *Demux 2* that acts as a receiving demultiplexer to *drop* the received channels. The rest of the input is carried towards the output port *Express-Out* and then connected to the *Express-In* input port. *Demux 1* separates (demultiplexes) the stream of incoming wavelengths with defined channel spacing. Optical switches are then used to decide whether to block any channel, or to pass it as an express. The express-channels are passed directly towards the *Line-Out* output port, while in place of the blocked channels, new signals are added of the same wavelengths through the *add* ports.

3.1.2. Advantages over other Structures

PLC-based ROADMs have attracted a lot of attention because of their simpler and more efficient manufacturing approach as compared to the MEMS [LiLi02, Ligh05], or hybrid approach [Metc05b, JWSS06]. There are no moving parts inside them and the overall manufacturing approach is similar to those of semiconductor Integrated Chips (ICs) that helps the vendors to go for mass production. The manufacturers usually integrate all the functional components of the subsystems including AWGs, VOAs, switches and taps into one chip and once the fundamental design becomes complete, they can print it on a silicon wafer again and again that in turn, reduces the total system costs. The other advantages of this technology are their potential compact size and their ability to support high channel count applications (8-40 channels). They also offer reduced initial installation costs, less operating complexity and seamless capability for future expansions.

3.1.3. Proposed Design Improvements

The major effort on designing the PLC-based architecture is to limit the loss, especially for the express-channels. In the reconfigurable add-module, there are two AWGs for which the loss is around 7 dB, while the technology is mature enough to develop almost loss-less (1dB to 2dB) thermo-optic switches. Hence, the loss for express-channels mainly depends on choosing the type of splitter/coupler installed just after the *Line-In* input port. For the PLC-ROADM (available at CRC), a 30%/70% splitter is chosen to divert 70% of the total power towards the reconfigurable add-module making the total loss for express-channels around 10 dB to 12 dB, while for drop-channels the loss will be around 8.7 dB. However, the loss for add-channels remains close to 5 dB to 6 dB regardless the type of the splitter used.

Note that in a DWDM network with closely spaced channels, it is important to maintain equal power levels among different channels. Because in dynamically provisioned optical network with multiple adding and dropping of wavelengths, there will be a significant mismatch in the optical power levels among different channels. Such an irregular optical power level will create a lot of difficulty, especially for the low-powered channels because of the effect of crosstalk and other nonlinear issues. Moreover, each amplifier in a network works within a particular input power range. The combined power of all channels arriving at the input of the amplifier can be out of that operating range because of the irregularity at the individual channel power level. In such case the corresponding amplifier will drive into saturation and the system will behave like a single line failure. Hence, to avoid such anomalies, a common control interface can be developed for the PLC-ROADM architecture through Inter-Integrated Circuit (I2C) ports that provides control over the 2x1 optical switches and VOAs placed within the add-module. It can also be used to monitor the power level of different channels by placing tap monitors on desired locations. With the help of VOAs and internal tap monitors, it is possible to develop a dynamic power balancing system that will always ensure equalized power levels among different express- and add-channels.

The conventional recommendation [RhTo03, SoCh03, BoSh02, LiLi02, RhTo02] is to mount optical amplifiers with the ROADM module for the purpose of pre- and post-amplification as indicated earlier in Chapter 2 (Fig. 2.1). However, the gain and other parameters of the pre-amplifier depend more on the length and the type of the fibre used before the corresponding ROADM node [Joha96]. Regarding the post-amplifier, it will be demonstrated in the later sections that signals coming out of the ROADM node are strong enough to travel a significant amount of distance before they are required to be amplified. Hence, it is better to equip each fibre segment with the necessary amplifiers and dispersion compensation modules leaving the ROADM module alone as presented in Fig. 3.1.

3.2. Network Operation

The detailed design layout for the next generation metro optical network equipped with ROADMs is presented in this section as depicted in Fig. 3.2. For simplicity, only a unidirectional ring network is presented where each node consists of a single PLC-based ROADM module. Note that, due to the integrated functionalities of the ROADM subsystem, there is no need for additional multiplexers/demultiplexers, or Photonic Cross-Connects (PXCs) within the node structure. Service providers can use the passive drop module as the receiving demultiplexer while transmitting new channels using the reconfigurable add ports.

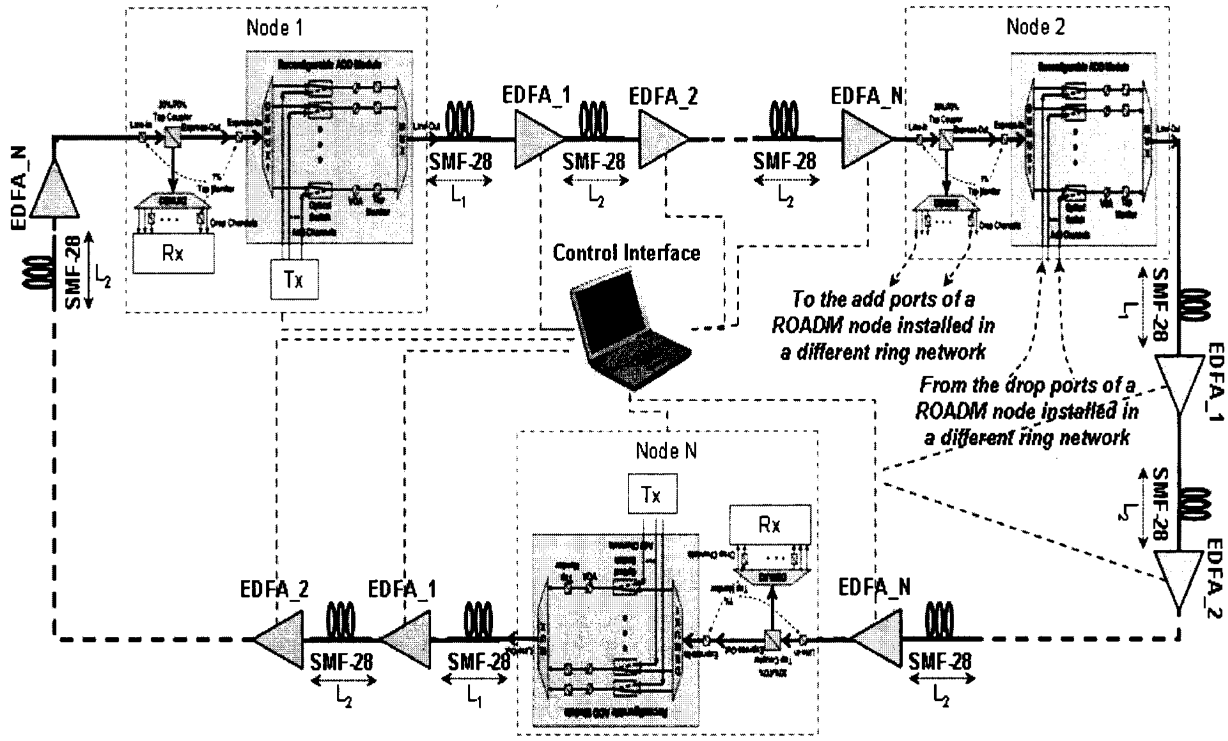


Fig. 3.2. PLC-based ROADMs in the metro optical network

Single Mode Fibre (SMF) spans equipped with Erbium Doped Fibre Amplifiers (EDFAs) are used to connect the ROADM nodes in the ring network. Since the optical power of the newly added channels are usually stronger than that of the express-channels, service providers can use the internal VOAs of the ROADM module to balance the power levels so that all the channels coming out of the node have the same level of optical power. ROADM modules can also be used to setup transparent interconnections with other ring networks which will be described in detail in Chapter 5.

It is important to note that the EDFAs installed in the system, work within a particular input power range. The length of the fibre segments mainly depends on the input power range and the gain of these EDFAs. Considering the channels coming out of the node have attained the same power level, the combined channel power must be within the input power range of the EDFA. Otherwise, the EDFA will not work and the system will behave like a single line failure.

For an *N-channel* system, denote $P_{N_{dBm}}$ as the combined power all the channels coming out of the node, $P_{Ch_{mw}}$ as the power of each channel in mW. Also denote $P_{EDFA_{MAX}}$ and $P_{EDFA_{MIN}}$ respectively as the maximum and the minimum power range within which the EDFA can work properly. Then the combined power at the input of the EDFA, $P_{EDFA_{IN}}$ can be expressed as:

$$P_{EDFA_{IN}} = P_{N_{dBm}} = 10Log_{10}\left(N * P_{Ch_{mw}}\right);\ P_{EDFA_{MAX}} \geq P_{N_{dBm}} \geq P_{EDFA_{MIN}} \qquad (3.1)$$

From (3.1), the required power level for each channel can be obtained as:

$$\begin{aligned} P_{EDFA_{IN}} &= 10Log_{10}\left(N*P_{Ch_{mw}}\right) \\ \Rightarrow\ Log_{10}\left(N*P_{Ch_{mw}}\right) &= \frac{P_{EDFA_{IN}}}{10} \\ \Rightarrow\ P_{Ch_{dBm}} &= P_{EDFA_{IN}}|_{dBm} - 10Log_{10}N \end{aligned} \qquad (3.2)$$

where $P_{Ch_{dBm}}$ defines the power of each channel in dBm. If the EDFA works within the power range defined by $P_{EDFA_{MIN}} \leq P_{EDFA} \leq P_{EDFA_{MAX}}$, the power level of each channel must have to be within the range of $P_{Ch_{MIN}} \leq P_{Ch} \leq P_{Ch_{MAX}}$. Hence,

$$P_{Ch_{dBm}|MIN} = P_{EDFA_{dBm}|MIN} - 10Log_{10}N \qquad (3.3)$$

and $$P_{Ch_{dBm}|MAX} = P_{EDFA_{dBm}|MAX} - 10Log_{10}N \qquad (3.4)$$

Considering 0.2 dB/km power loss through the SMF-28 fibre and neglecting dispersion and other non-linear effects, the maximum possible length of the fibre segments will be,

$$L_{1|MAX} = \frac{P_{N_{dBm}} - P_{EDFA_{dBm}|MIN}}{0.2} \tag{3.5}$$

$$L_{2|MAX} = \frac{Gain_{EDFA_{dB}}}{0.2} \tag{3.6}$$

where L_1 is defined as the length of the first fibre segment between a node and an EDFA, while L_2 defines the fibre span between two EDFAs. Both $L_{1|MAX}$ and $L_{2|MAX}$ are the maximum possible fibre spans for L_1 and L_2 respectively regardless of the transmission speeds and other non-linear effects.

A numerical example is presented below using parameters in Table 3.1.

TABLE 3.1. PARAMETERS FOR THE EXAMPLE

Name of Parameters	**Value**
Number of Channels, N	4
Power of the channels arriving at the input of Node 1	-13 dBm/channel
Losses through Node 1: Express channels	12 dB
Add channels	6 dB
Transmitted power	-3 dBm/channel
Maximum EDFA gain	20 dB
EDFA input power range	-26 dBm to -17 dBm
Losses in fibre	0.2 dB/km

Here, $P_{EDFA_{MIN}}$ = -26 dBm and $P_{EDFA_{MAX}}$ = -17 dBm. From (3.3) and (3.4), $P_{Ch_{MIN}} = -26 - 10Log_{10}(4) \approx$ -32 dBm; and $P_{Ch_{MAX}} = -17 - 10Log_{10}(4) \approx$ -23 dBm

Hence, the power of each channel at the input of the EDFA must be within the range of -32 dBm to -23 dBm. Since the express-channels acquire a loss around 12 dB through the ROADM node, each express-channel coming out of *Node 1* will maintain a power level of around -25 dBm. However, each newly added channel at the output of *Node 1* will attain a power level of around -9 to -10 dBm (considering transmitted power -3 to -4 dBm plus loss of -6 dB). Internal VOAs are then required to be activated to attenuate the newly transmitted channels by 15 to 16 dB in order to make a balance among the power levels.

$P_{Ch_{mW}} = 0.003162$ mW; $P_{N_{dBm}} = 10Log_{10}(4 \text{ x } 0.003162) \approx$ -19 dBm. From (3.5) and (3.6),

$$\mathrm{L}_{1|\mathrm{MAX}} = \frac{P_{N_{dBm}} - P_{EDFA_{dBm}|MIN}}{0.2} = \frac{-19-(-26)}{0.2} = 35 \text{ km} \text{ ; } \mathrm{L}_{2|\mathrm{MAX}} = \frac{Gain_{EDFA_{dB}}}{0.2} = \frac{20}{0.2} = 100 \text{ km}$$

Hence, the maximum possible length of the fibre segment between the node and the *EDFA1* will be around 35 km (= $L_{1|MAX}$), while between *EDFA 1* and *EDFA 2*, it will be around 100 km (= $L_{2|MAX}$). However, in reality due to dispersion and other non-linear effects, both L_1 and L_2 are less than their maximum anticipated value as will be demonstrated in the Chapter 4.

3.3. Developing Simulation Models

Simulation models are developed especially for the PLC-ROADM module and other optical equipments. For every optical component, parameters of the developed model can easily be configured according to the designated module's available spec-sheet. In order to reflect the pragmatic scenarios, several other models have also been developed to control the Extinction Ratio[§] (ER), and also to provide adjacent channel crosstalk[**] and other non-linear effects such as Chromatic Dispersion[††] (CD), Polarization Mode Dispersion[‡‡]

[§] ER is defined as the ratio of the optical power of two levels – the power generated for the logic level 1 and the power generated when the logic level is 0.

[**] Crosstalk is defined as the presence of unwanted effect of adjacent channels in that corresponding channel [RaSi02].

[††] CD defines the dispersion caused by the variation in refractive index of the glass in the fiber and due to changes in the distribution of light between the core and the cladding of a single-mode fiber.

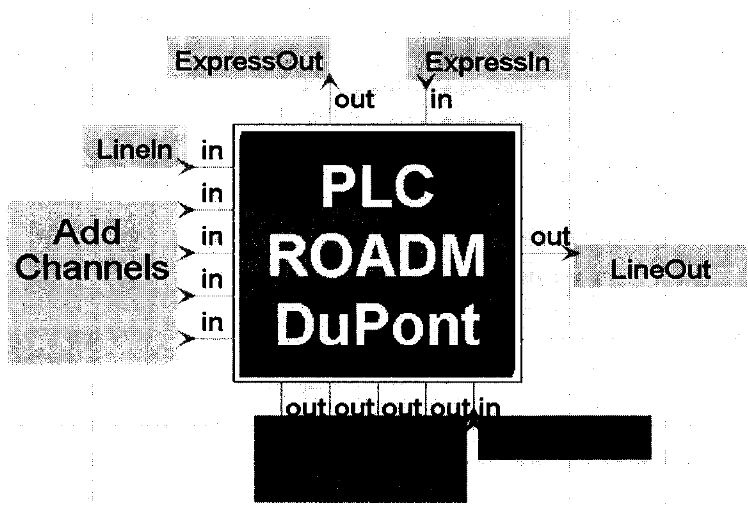
[‡‡] PMD occurs when different planes of light inside a fiber travel at slightly different speeds and create problem while transmitting data at high speeds.

(PMD), and so on. The next few sub-sections describe the steps followed for developing the simulation models for the PLC-based ROADM module and all other available components in a reconfigurable AON.

3.3.1. Model for PLC-based ROADM

Using VPI, we have developed a *Galaxy*[§§] module for a 4-channel PLC-based ROADM module (see Fig. 3.3a). The model is developed according to the spec-sheet of a 16-channel PLC-based ROADM module manufactured by DuPont Photonics. The detailed characteristics of the DuPont's *i*ROAD™ 1600 ROADM module is available at Appendix A. The parameter setting for the ROADM Galaxy is depicted in Fig. 3.3b that exactly follows the ROADM specification sheet depicted in Table A.1. Although the simulation model contains only 4-channels (shown by *ChannelNumber* in Fig. 3.3b), it can be easily upgraded to higher number of channels by cascading the 4-channel galaxy modules. The other *Common* parameters e.g. *ChannelSpacing* and *Passband* define the spacing between adjacent channels and bandwidth of the internal AWGs respectively.

[§§] A Galaxy in VPI [VPIP] is defined as the hierarchical design block that may contain many other galaxies and optical equipments. The simplest form of a Galaxy is just a grouping of several optical equipments.



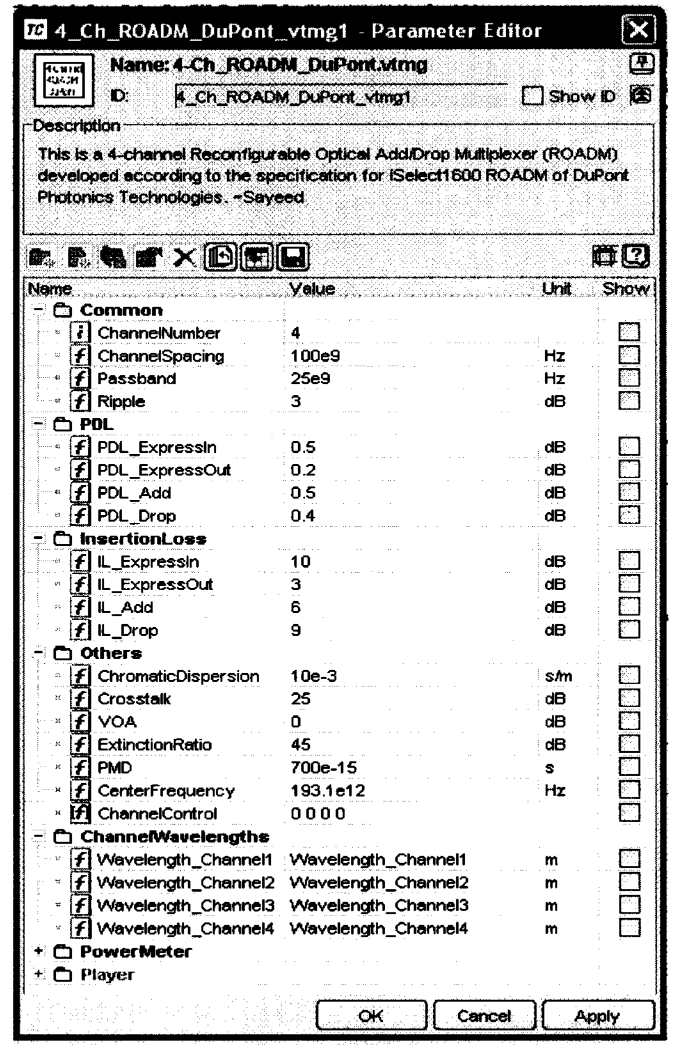


Fig. 3.3(a). Developed galaxy module for Dupont's ROADM, (b). Parameters of the ROADM module

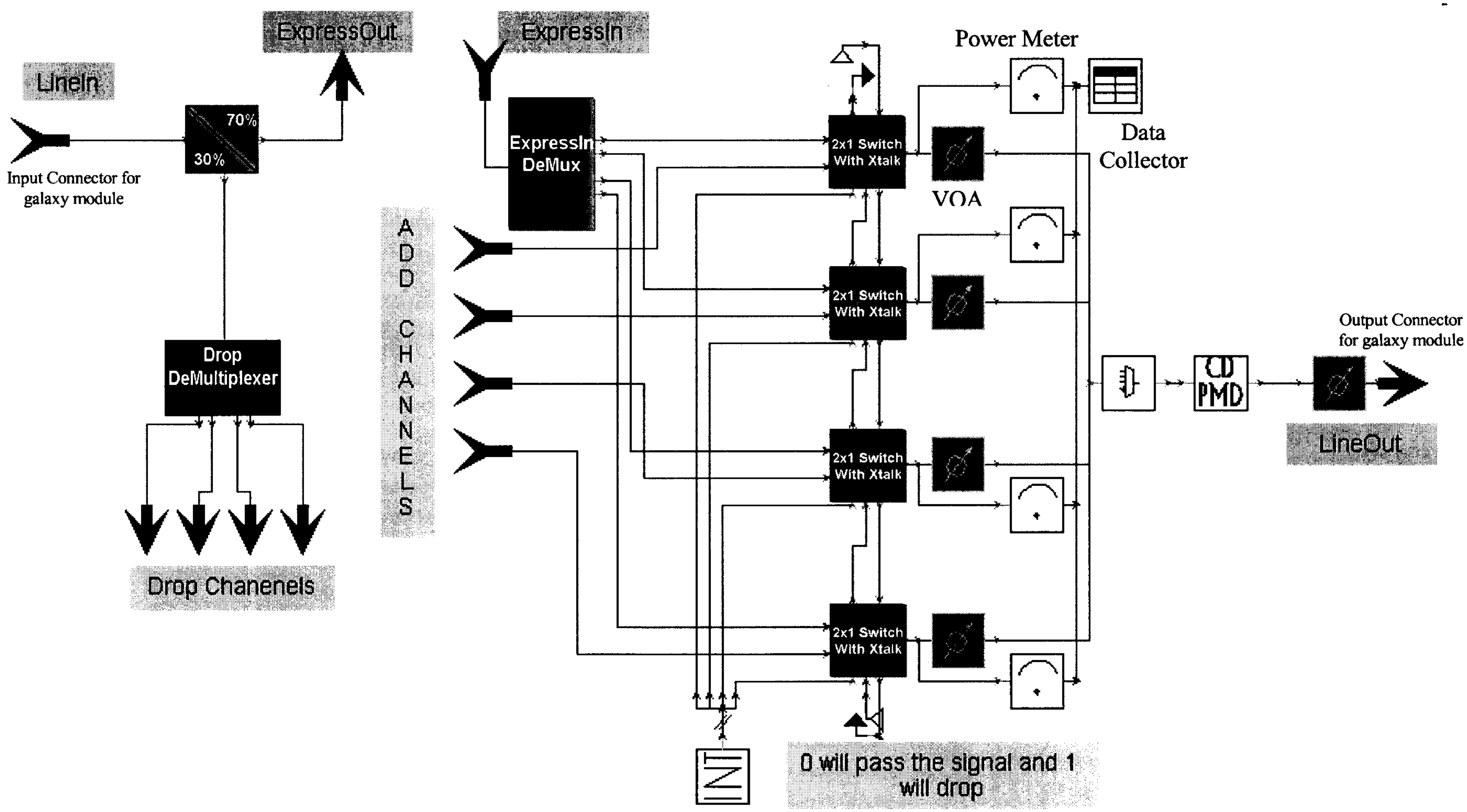


Fig. 3.4. Internal structure of the ROADM galaxy shown in Fig. 3.3(a)

As shown in Fig. 3.3b, the characteristics of the ROADM model can easily be reconfigured by assigning different values at the parameter settings. The parameter window (Fig. 3.3b) allows the users to assign Polarization Dependent Losses (PDLs) and Insertion Losses (ILs) for different segments of the ROADM module. The *Other* features of the model include assigning specific crosstalk, extinction ratio, dispersion parameters and controlling the internal VOAs and optical switches (by *ChannelControl*). The rest of the parameters are for assigning specific wavelengths for different channels, and also for activating internal tap monitors (by the *PowerMeter* section in Fig. 3.3b). The internal construction of the ROADM *Galaxy* is shown in Fig. 3.4. The *Galaxy* contains few other internal modules including a 70%/30% Coupler, the Drop-/Express-In Demultiplexers, the 2x1 Optical Switches, the Chromatic Dispersion (CD) / Polarization Mode Dispersion (PMD) Generator Modules, the Crosstalk Generators, and the Extinction Ratio (ER) Controllers. These will be described in sequence in the following few subsections.

3.3.1.1. The 70%/30% Coupler

A 70%/30% coupler is setup in front of the ROADM module to provide the necessary Insertion Losses (ILs) and Polarization Dependent Losses (PDLs) for the *Line-In* to *Drop* and *Line-In* to *Express-Out* channels. Fig. 3.5 shows the internal structure of the *Galaxy* module developed for the 70%/30% coupler. A logical splitter is used to split the channels with equal power (no power loss) and then two different types of attenuators are used to provide the required losses. The polarization attenuator and the optical attenuator cover the losses for *PDL_Drop*, *PDL_ExpressOut*, and *IL_Drop, IL_ExpressOut* respectively for both of the drop- and express-channels.

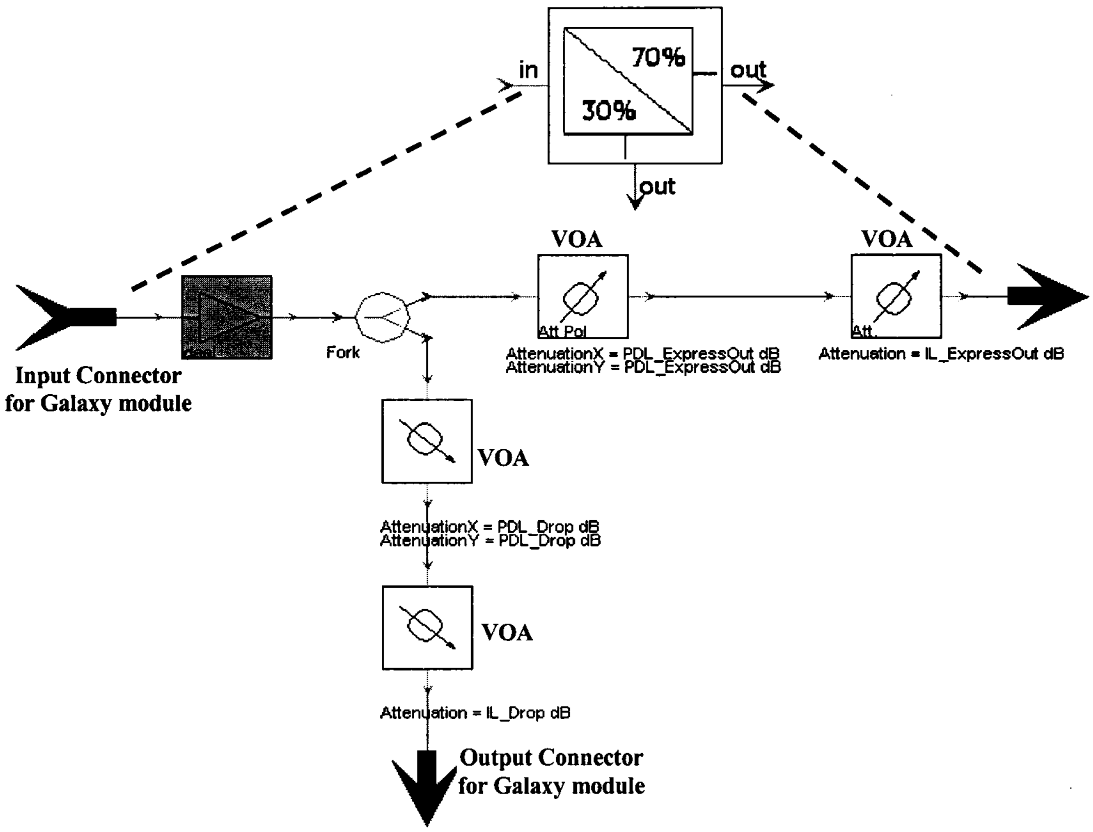


Fig. 3.5. The 70%/30% coupler Galaxy module and its internal construction (indicated by the dotted line)

3.3.1.2. Drop-Demultiplexer / Express-In Demultiplexer

A specific demultiplexer module is developed using *Gaussian* filters for the *Drop* channels as shown in Fig. 3.6. The bandwidth of the Gaussian filters is specified by the parameter *Passband* of the ROADM module. There is also a *CD-PMD* module within the *Drop Demultiplexer* that provides the specified CD and PMD for all of the drop-channels. There are an *ER-Controller* and a *Crosstalk-Generator* installed for each channel that limit the ER and provide the required adjacent channel crosstalk according to the ROADM's specification sheet.

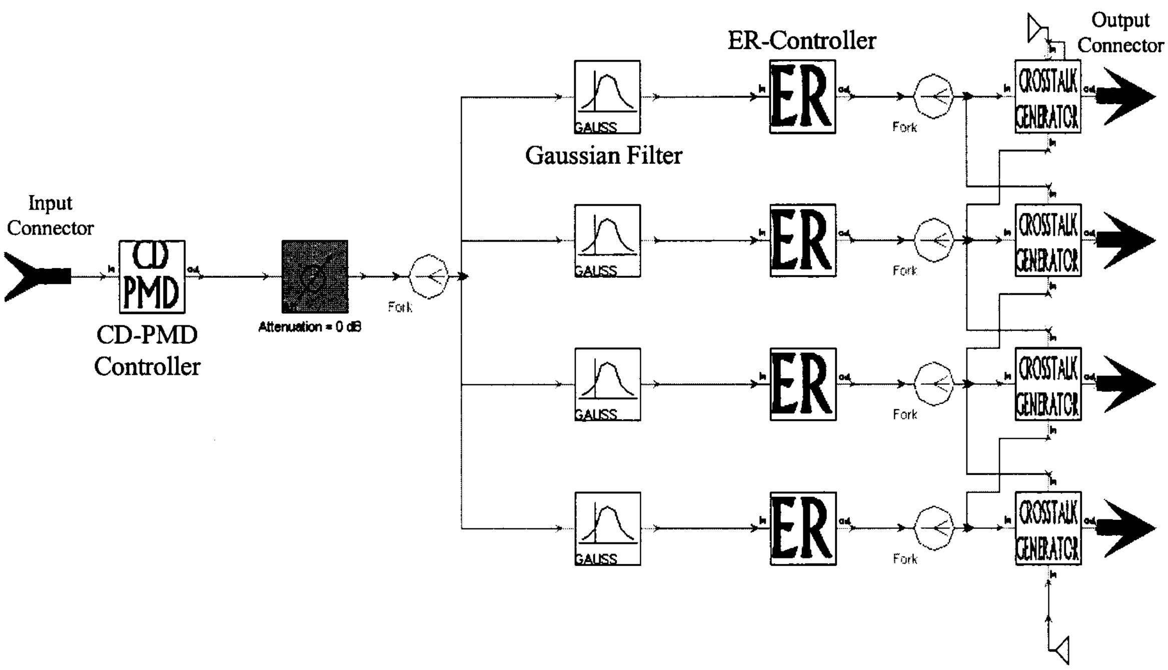


Fig. 3.6. Internal structure of the Drop-Demultiplexer

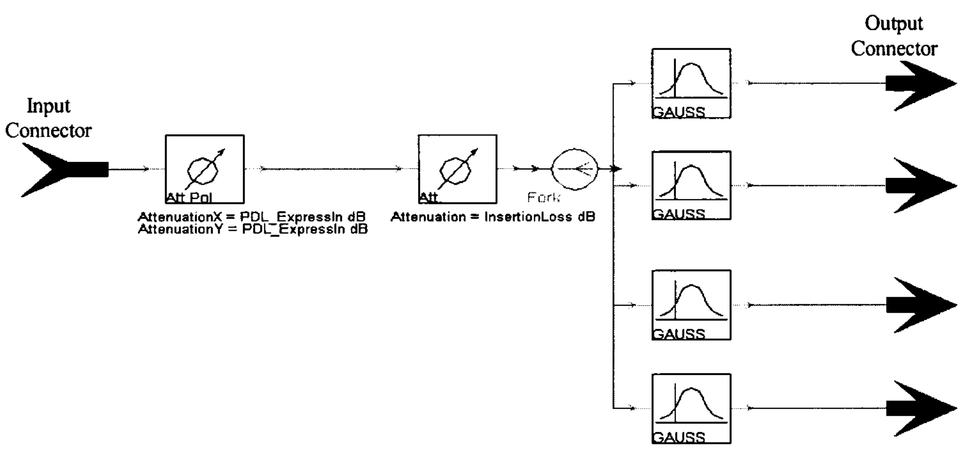


Fig. 3.7. Schematic for Express-In demultiplexer

However, the demultiplexer model developed for the express channels after the *Express-In* port is a simple, and almost an ideal demultiplexer as depicted in Fig. 3.7. The module contains *Gaussian* filters of order *1* that separate the channels almost ideally according to the specified bandwidth. The bandwidth of the filters is set at *4*BitRateDefault,* while the *ActiveFilterBandwidth* is made equivalent to *2*ChannelSpacing.*

3.3.1.3. *The 2x1 Optical Switch*

The *2x1* optical switch selects either the add-channel, or the express-channel. The *ER-Controllers* (both *ER* and *ER-pass* are same) are also setup for these channels. In the path of the add-channel, proper attenuators are introduced in order to obtain the corresponding IL and PDL. An ideal *2x2* optical switch is used to perform the switching as shown in Fig. 3.8a.

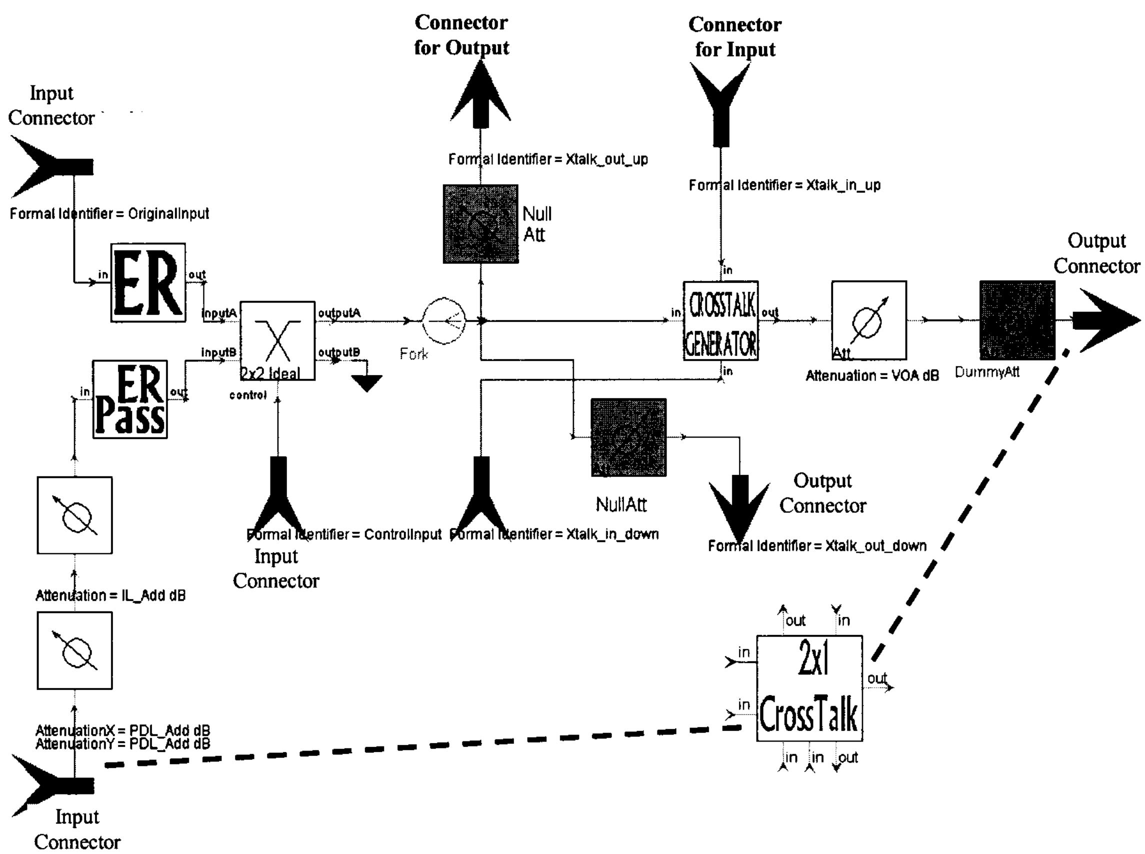


Fig. 3.8. The internal structure of the 2x1 optical switch Galaxy module

The optical switch module receives the control signal from the ROADM's parameter *ChannelControl* and acts in cross-state, or in bar-state for receiving a *1*, or a *0* respectively. After selecting the outgoing channel, a controlled amount (25dB) of crosstalks is introduced from the adjacent channels using the *Crosstalk-Generator* module. Outputs are taken from the corresponding channel in order to introduce crosstalk effects to other adjacent channels. Finally, an attenuator is inserted as a VOA to provide the necessary power adjustment for each channel. There are couple of dummy attenuators (shaded ones) inserted within the switching module only for connection purposes.

3.3.1.4. The Chromatic Dispersion (CD) / Polarization Mode Dispersion (PMD) Module

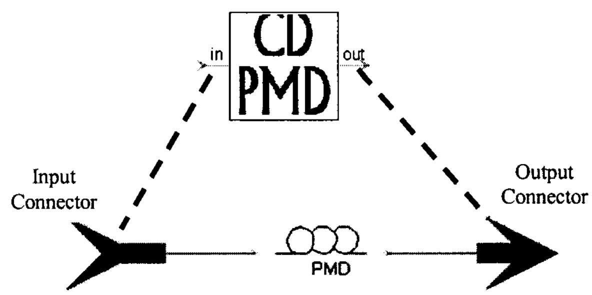


Fig. 3.9. The internal structure of the Chromatic and Polarization Mode Dispersion Galaxy module

The chromatic and polarization mode dispersion module is developed using a *PMD* fibre as shown in Fig. 3.9. The length of the fibre is set at 1 km while the parameters *Dispersion* and *PolarizModeDisp* are set as below:

$$\text{Dispersion} = (\text{ChromaticDispersion})*1e^{-6}\ \text{s/m}^2 = \frac{\text{ChromaticDispersion}}{1000^2}\ \text{s/m}^2$$

$$\text{PolarizModeDisp} = \text{PMD}/\ 31.623\ \text{s/m}^{1/2} = \frac{\text{PMD}}{\sqrt{1000}}\ \text{s/m}^{1/2}$$

According to the ROADM spec-sheet (Appendix A), the value for chromatic dispersion and PMD are set at their maximum values at 10 ps/nm and 0.7 ps respectively.

3.3.1.5. The Crosstalk Generator

The crosstalk generator module is shown in Fig. 3.10 that introduces specific adjacent channel crosstalk to the designated channel. The ROADM subsystem module provides an adjacent channel isolation of 25 dB. In order to model this, the adjacent channels are shifted by **180°** and then attenuated by 25 dB before mixing them with the corresponding channel. The signals are then re-sampled at the same sampling rate and centre frequency of that channel, but restricting the bandwidth at 320 GHz. However, the adjacent channels are phase shifted by 180° in order to impose the highest crosstalk effect.

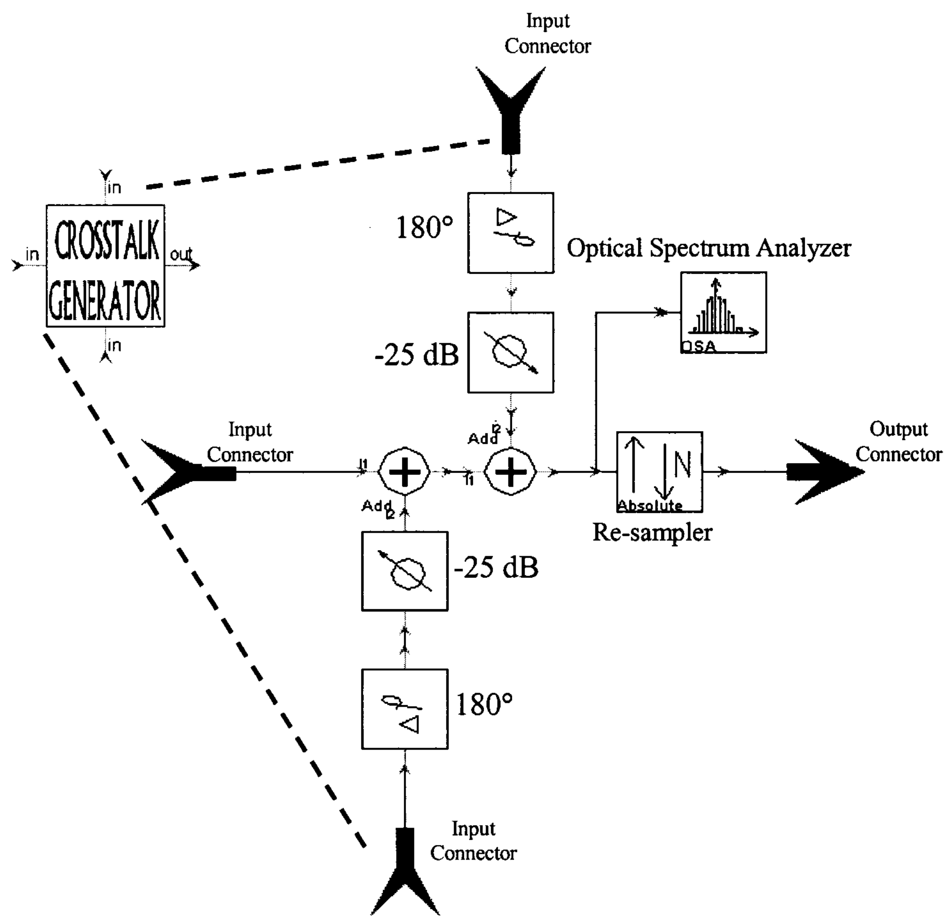


Fig. 3.10. The internal construction of the Crosstalk Generator Galaxy module

3.3.1.6. The Extinction Ratio (ER) Controller

The ROADM module provides an extinction ratio of 45 dB that means any signal coming with an ER more than 45 dB will be restricted to that limit, while the signals coming with an ER less than 45 dB will be simply passed away. Fig. 3.11 shows the *galaxy* module developed for the *ER-Controller*. Such modules are inserted both in *Drop-demultiplexer* and *2x1 optical switches* in order to control and monitor ERs of the drop-channels and add-/express-channels respectively.

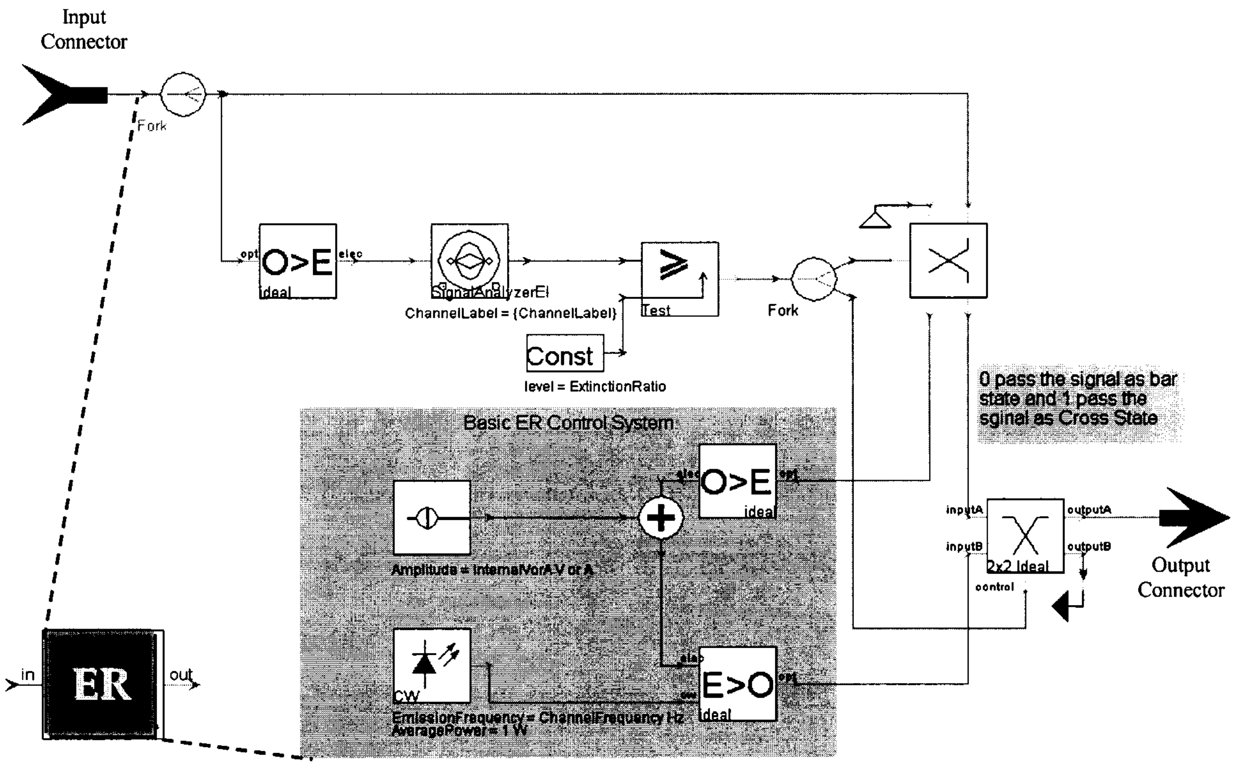


Fig. 3.11. The internal structure of the Extinction Ratio controller Galaxy module

In the ER controller shown in Fig. 3.11, an optical signal is first received and diverted towards an ideal Optical-Electrical (O>E) converter by a logical fork. A signal analyzer computes the ER of the incoming signal and a *comparator (≥)* module compares that value with the *Extinction Ratio (45 dB)* specified within the *Const* module. If the ER of the incoming signal is more than 45 dB, the *comparator* module generates a logic level *1* that switches the original optical signal to pass through the basic ER control system. In any other case, the signal will simply be passed towards the output of the module without any kind of alternation. In the basic ER control system, the original optical signal is again converted to its ideal electrical form. An external Voltage (V)/Current (C) is added with the electrical signal to limit the power level for logic *1*. The value of the external V/A is highly dependent on the power level of the original optical signal. In order to fix the extinction ratio at 45 dB, the following values are selected for various paths as presented in Table 3.2:

TABLE 3.2. INTERNAL V, OR A SETUP FOR VARIOUS PATHS

Channels	Power Level before the ER controller	Internal V or A for ER controller
Add	- 6 dB	$8.0e^{-9}$
Drop	- 9 dB	$4.0e^{-9}$
Express	- 12 dB	$1.0e^{-9}$

The electrical signal is then converted back to optical form using an ideal Electrical-Optical (E>O) converter and a Continuous-Wave Laser (Laser CW) with an average power of 1 watt. The external Laser CW (setting the power 1W) does not alter the original power level of the incoming signal and the signal comes out finally off the ER-Controller module with an ER of 45 dB without any change in its original optical power level.

3.3.2. Model for Reconfigurable AON

The layout for the reconfigurable All-Optical Network (AON) has been demonstrated earlier in Fig. 3.2. To simulate such next generation network, simulation models are required to be developed for several other optical components e.g. Transmitters (Txs)/Receivers (Rxs), EDFAs and SMF-28 fibres. Models are also developed for PXCs and AWGs in case required to inaugurate more flexibility to the network. All the developed models are configured according to their commercially available spec-sheet. Two separate models are developed for the EDFAs installed at the first and second stage respectively. Both the EDFA models insert additional Amplifier Spontaneous Noise (ASE) into the system to simulate the impacts in experimental scenarios. The detailed simulation model developments of all the components and their parameter settings are presented in Appendix B.

3.4. Performance Measures

The system performance is evaluated both by measurements and by simulations in terms of two measures: the Q-factor and the Optical Signal-to-Noise Ratio (OSNR). Mathematically, the Q-factor for an optical signal is simply the integration of Gaussian error [GuAn02] and can be measured from the phase and amplitude of the received electrical signal. The Q-factor also provides a qualitative factor of the system's overall performance because it is a function of the signal's OSNR [GuAn02]. It provides the minimum Signal-to-Noise Ratio (SNR) required to achieve a specific Bit Error Rate (BER) of a given signal. The BER for an optical signal can be described by

$$\begin{aligned} \text{BER} &= P(1)P(0\,|\,1)+P(0)P(1\,|\,0) \\ &= \frac{1}{2}\left[P(1)erfc\left(\frac{I_1 - I_{th}}{\sqrt{2}\sigma_1}\right)+P(0)erfc\left(\frac{I_{th} - I_0}{\sqrt{2}\sigma_0}\right)\right] \end{aligned} \tag{3.7}$$

where *P(1)* and *P(0)* are the probabilities that a *1*, or a *0* is transmitted, while *P(0|1)* and *P(1|0)* are the probabilities that a *0*, or *1* is received when actually a *1*, or *0* was sent respectively. The parameters I_1 and I_0 are the induced photocurrent from the detector and σ_1 and σ_0 are the Root-Mean-Square (RMS) noise of a *1*, or *0* bit respectively. I_{th} defines the threshold current with which the received bit is supposed to be compared to decide whether it is a *1*, or *0*.

The *erfc* is the complementary error function and is defined by $erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-u^2} du$.

Considering equal probability for *1* and *0*, $P(0) = P(1) = \frac{1}{2}$,

$$\text{BER} = \frac{1}{4}\left[erfc\left(\frac{I_1 - I_{th}}{\sqrt{2}\sigma_1} \right) + erfc\left(\frac{I_{th} - I_0}{\sqrt{2}\sigma_0} \right) \right]$$

If the optimum threshold current, I_{th} is considered as $I_{th} = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1}$, the minimum BER for the channel can be obtained as $\text{BER} = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}} \right)$. Hence, the Q-factor can be obtained from the BER of the received signal using the relation:

$$Q = \sqrt{2} * erfc^{-1}(2 * \text{BER}) \quad (3.8)$$

Obviously, the higher value of the Q-factor the better the BER. In order to satisfy the Forward Error Correction (FEC) requirement, the minimum value of Q-factor is taken to be 7.94 (BER $\approx 10^{-15}$) [RhTo02]. Note that the Q-factor obtained in (3.8) is a unit-less quantity and therefore can be expressed in decibels (dB), i.e. $Q_{dB} = 20\log_{10} Q$.

In the experimental measurements, a Bit Error Rate Tester (BERT) is primarily used to measure the Bit Error Rate (BER) of the optical signals. The measured BER is then converted to Q-factor using (3.8) which is an easier and a better presentation of BER. However, obtaining a steady value of BER in real-time measurement for the complete sequence of the transmitted pattern (from *BERT*) usually takes very long time [GuAn02] (e.g. in a metro network scenario with a pseudo random bit sequence of 2^{23}-1 transmitting at 2.48 Gbps, only 6 errors were observed by me over a period of 48 hours and the value of BER was still not stable). Hence in our simulation, the BER of a channel is measured using

Gaussian approximation method [Agra92, WaKi04] and then converted to Q-factor using (3.8).

The OSNR is another important parameter associated with a given optical signal. In our measurements, an Optical Channel Performance Monitor (OCPM) [BaIn06] is used to obtain OSNR of optical signals in real-time. In the simulation, signal power can be measured at each channel, while the noise power can be measured separately between two consecutive channels. Such noise measurement requires dynamic Resolution Bandwidth (RBW) settings to get more accurate results, especially in case of closely spaced channels. However, in simulation, it is very difficult to obtain the optimum RBW settings for both signal and noise measurement from the channels' optical spectrum. Hence, in simulation OSNR is obtained directly from the Q-factor using the following relation specified in [GuAn02]:

$$OSNR_{dB} = Q_{dB} - 10\log\frac{B_o}{B_e} \tag{3.9}$$

where B_o is defined as the RBW of the photo-detector and B_e is defined as the electrical bandwidth of the receiver filter. One can see that $OSNR_{dB}$ for a given signal is somehow proportional to the Q_{dB}-factor of that signal. In the simulation, B_o is 0.1 nm (12.5 GHz), while B_e is selected as 35 GHz. However, the above relation in (3.9) does not consider distortion and is true only when OSNR >>1. More accurate descriptions on measuring OSNR can be found in [DuSt01].

3.4.1. Simulation Environment

We conduct our simulations at a sampling rate of 320 GHz and at a transmission speed of 2.5 Gbps unless otherwise specified. Each simulation point presented in this thesis is the average (or mean) of 4 runs using different seeds at the transmitters (for generating pseudo random bit patterns), amplifiers (for generating spontaneous emission noise), and at the receivers (inside the photodiode for detecting bit patterns). The standard deviation among the simulation results for different seed runs is less than 2% (for both Q-factor and OSNR) with a maximum variation of 0.5 for Q-factor, and 0.3 dB for OSNR at a confidence interval [Stds06] of 95%.

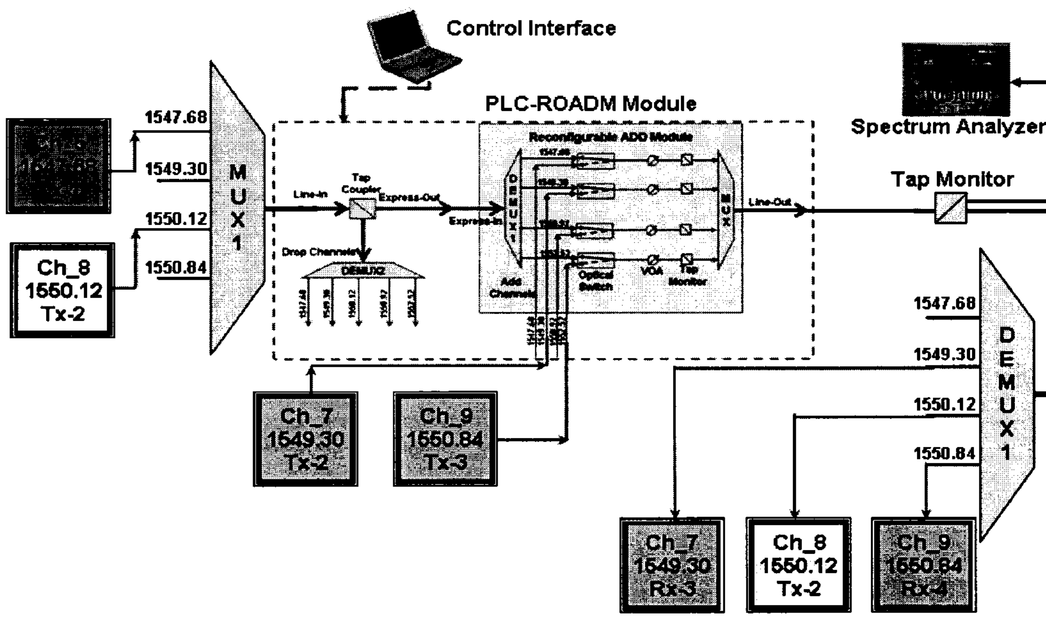


Fig. 3.12. Simulation setup for developed ROADM model (schematic from VPI is presented in Fig. 3.13)

3.4.1.1. Testing the Functionality of Simulation Models

In order to check the functionality of the different sections of the developed ROADM and other system models, a setup has been simulated that is demonstrated in Figs. 3.12 and 3.13. Four channels of C-band (Conventional Band) respectively at 1547.72 nm (Channel-5), 1549.32 nm (Channel-7), 1550.12 nm (Channel-8) and 1550.92 nm (Channel-9), are transmitted in order to emulate a metro network scenario where Channel-5 is dropped, Channel-8 is made expressed, while Channels 7 and 9 are added externally through the ROADM's add-ports.

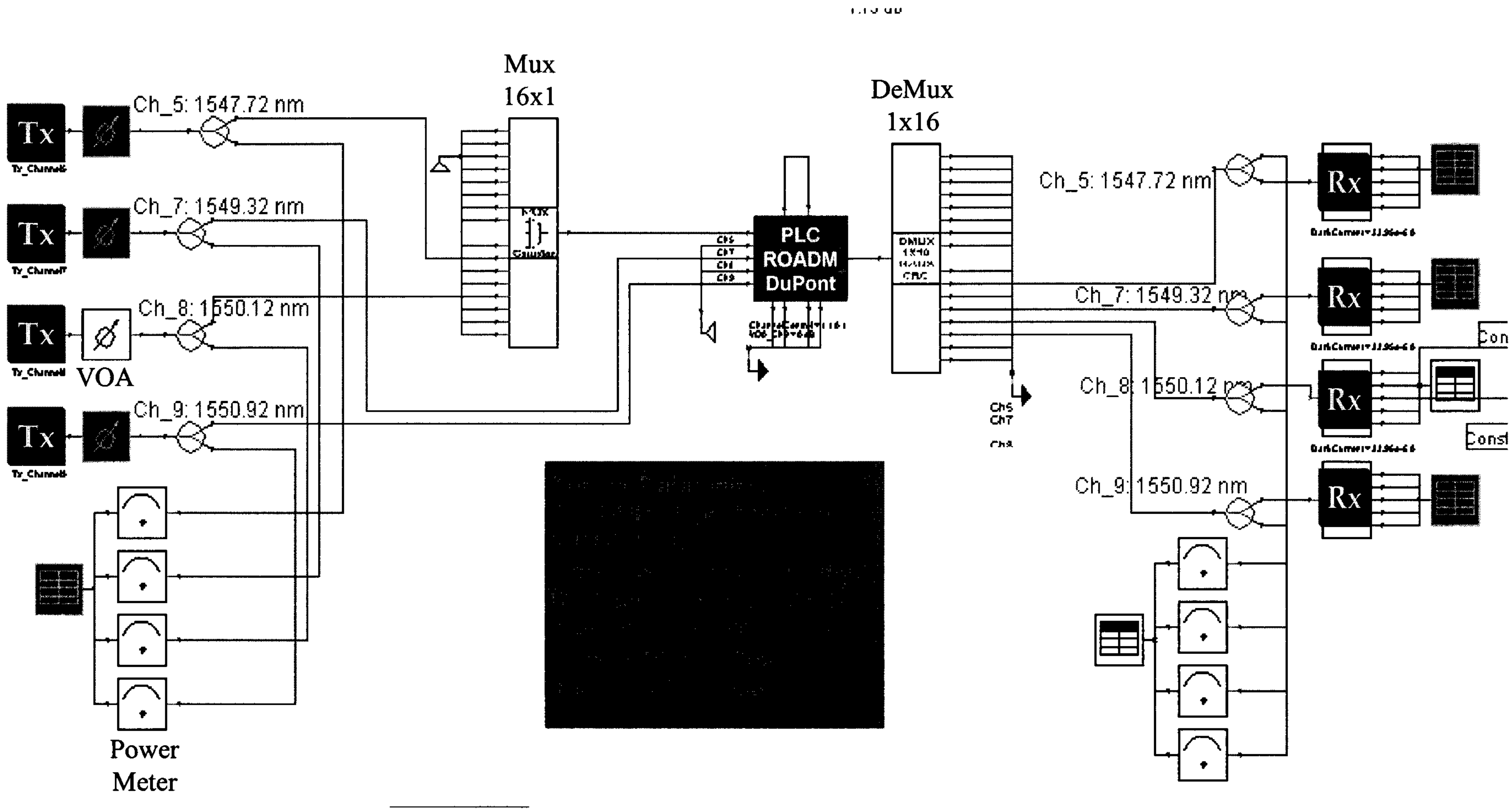


Fig. 3.13. Simulation setup developed in the VPI simulation tool [VPIP06] for the setup shown earlier in Fig, 3.12

The *ChannelControl* of the ROADM model is selected as ***1 1 0 1*** that performs the required add/drop operation. Two AWGs (*Mux 1* and *DeMux 1*) are installed in order to provide multiplexed input to the ROADM model and also to demultiplex signals coming out of the module respectively. Since Channel-5 is dropped from the network, and both Channels 7 and 9 are much stronger than the express-channel, only the performance of the weaker Channel-8 is measured in order to characterize the models performance for the worst case scenario. Simulations have been run by varying the adjacent channel crosstalk level of the ROADM model only while transmitting signals at different extinction ratios. After obtaining the BER measurements from the simulations, performance of the model is evaluated in terms of Q-factor. This is depicted in Fig. 3.14.

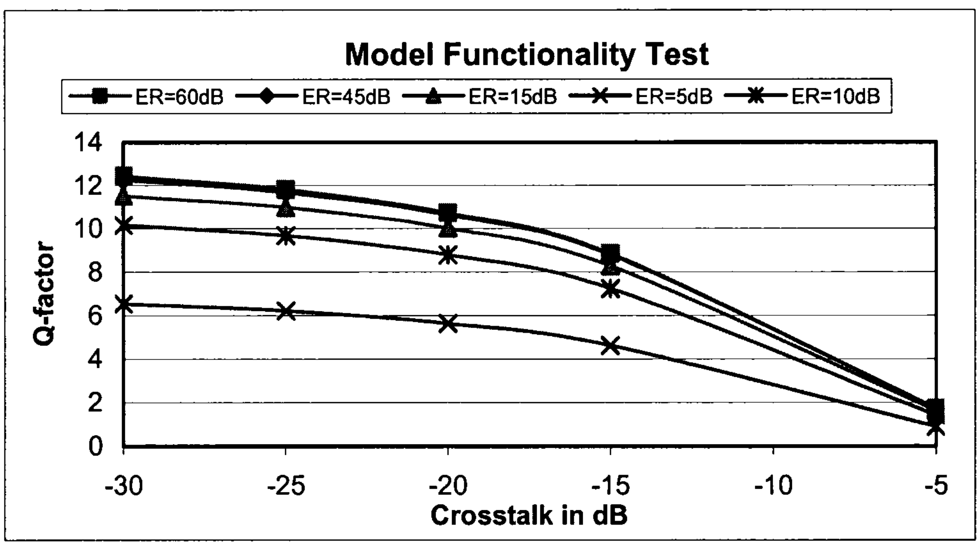


Fig. 3.14. Performance measures in terms of Q-factor for Channel-8 only

Examine the performance curve for ER = 15 dB of the transmitted signal. The Q-factor of the signal improves (increases) as the adjacent channel crosstalk decreases from -5 dB to -30 dB. The simulation has been also run for different other values of extinction ratios of the transmitted signals whose performance curves follow the similar characteristics. However, for a fixed adjacent channel crosstalk e.g. -20 dB, the Q-factor improves with the increase in Extinction Ratio (ER) of the transmitted signal. The ER-controller in each channel within the ROADM model limits the ER of the incoming channel to 45 dB (i.e., any higher ER value has no further effect on the Q-factor) as we have designed in our simulation model according to the PLC-based ROADM module's spec-sheet (see Appendix A). Therefore, almost the same results are obtained for signals with an ER more than 45 dB as displayed by the curve ER=60dB that closely follows the curve obtained for ER=45dB. This, in fact, demonstrates the functionality of the developed ER-controller. The simulation results also confirm the functionality of the crosstalk generator modules inserted within the drop-demultiplexer, and in the *2*x*1* switches that introduce the effect of crosstalk from adjacent channels to the corresponding channel.

Although the present model can handle only 4 express-/add-channels (to conform with CRC equipment with only 4 channels), it can be easily upgraded to add/drop, or express any number of wavelengths. The model can also be configured for handling channels with any number of channel spacing. For example, here Channels 7 to 9 are separated by 100 GHz (80 nm), while Channel-5 is 200 GHz away from Channel 7. The other parameters of the ROADM module such as chromatic- and polarization mode dispersion are so small that they do not provide any noticeable effect to the performance of the system. The ROADM model (shown in Fig. 3.3b) is currently specified according to the DuPont's PLC-based ROADM and can be easily reconfigured for any other similar type of ROADM modules.

3.5. General Assumptions

For the remainder of the thesis, the following assumptions pertain:

1) EDFA gains are fixed at their maximum because we want to investigate the performance of ROADM in terms of the maximum associated fibre span that will reduce the number of EDFAs in the field, and thus the overall CAPEX/OPEX.
2) White noise (having Gaussian distribution) is used because of simplicity and faster computation for all simulations that closely followed our experimental measurements.
3) OSNR >> 1 in all our simulations. Otherwise, our simulation would not provide accurate result.
4) The effect of chromatic- and polarization mode dispersions are negligible for low data rate (<10 Gbps) in the WSS module.

3.6. Concluding Remarks

In this chapter, two key issues about the functionality of a ROADM module have been addressed. The first one is the necessity of providing a power balanced system in a DWDM network, while the second one is about installing PLC-ROADMs without any accompanying amplifiers.

The detailed design layout for the next generation metro optical network is demonstrated where each node contains only a ROADM module without any supporting EDFAs. Mathematical equations have been developed that can be used to obtain the maximum possible length of the associated fibre segments based on the traffic demands in the optical networks. With the proposed design layout, a significant amount of fibre span can be inserted between the ROADM node and the EDFAs that will ultimately reduce the initial installation costs and operational expenditure for the overall network. However, the mathematical equations, presented in this paper for obtaining the maximum possible fibre span, do not consider factors such as channel spacing, crosstalk, dispersions and other non-linear effects for which the effective fibre length will be always less than their maximum anticipated value.

Furthermore, simulation models have been developed for the reconfigurable optical equipments in the AON system. Functionalities of the different developed models have been tested and presented in this chapter. Such simulation modules will obviously help the service providers to design and optimize their future metro optical networks without practically installing these expensive components. However, the developed simulation models are still need to be verified and calibrated with their real metro network performance so that service providers could rely on them. Hence in order to validate these simulation models, experimental test-beds are being developed that will be described in detail in Chapter 4.

CHAPTER 4: TESTING AND MODEL VERIFICATION

In order to verify the developed network simulation models, experimental test-beds have been designed and implemented with a prototype 16-channel PLC-based ROADM module. The ROADM module is first tested individually (Section 4.1) and then placed in an All-Optical Network (AON) system testbed for further testing (Section 4.2). Simulation models have also been developed for the reconfigurable AON system in order to verify the models with the experimental results.

4.1. Individual ROADM Module Testing

Before placing the ROADM into the AON testbed, it is important to know the characteristics of the ROADM itself. The characteristics of a device is usually supplied by its manufacturer in the spec sheet. However, it is still worthy to setup a testbed in order to verify all the characteristics mentioned in spec sheet, especially for a prototype device such as the *i*ROADM™1600 PLC-ROADM. The module is manufactured and supplied by DuPont Photonics [DuPo06] and can support 16 channels from 1544.52 nm (Channel-1) to 1556.55 nm (Channel-16) at 100 GHz channel spacing. The module is capable of adding/dropping or expressing any number of channels and supporting remote reconfiguration of these add/drop subset through a control interface. The objectives of this individual ROADM testing are:

1) To verify the wavelength plan at different add/drop ports and to check if the channels drift for a variation of temperature or any other reasons.
2) To obtain the amount of insertion losses at various paths for normal operating condition (In the spec sheet, only the maximum possible values are mentioned).
3) To observe if the internal VOAs when placed within the module would work linearly

for the range specified as 0 dB to 20 dB.

4) To check the performance of the internal tap monitors and optical switches.

5) To become familiar with the functionalities of the control interface associated with the ROADM module.

4.1.1. Experimental Setup

Fig. 4.1 shows the experimental setup implemented in order to verify the above mentioned objectives. A tunable laser, and an Optical Spectrum Analyzer (OSA) are used at various paths of the module. For example, the setup shown in Fig. 4.1 tests the parameters of the path *Express-In* to *Line-Out*. In order to test each channel (lightpath) of the ROADM module, the designated wavelength has been transmitted using the tunable laser and has been observed at the OSA. The Graphical User Interface (GUI) (not shown) of the ROADM has also been activated at the computer to maintain communication with the module through Inter-Integrated Circuit (I2C) / Parallel ports.

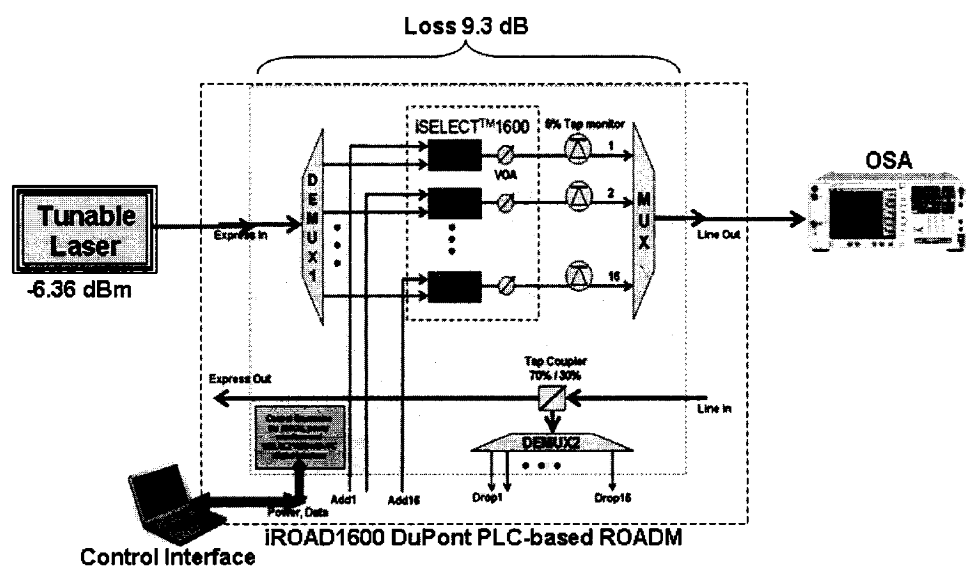


Fig. 4.1. Testbed implemented only to verify the parameters of the ROADM module individually.

Individual ROADM Test Results : **Date: December 14, 2005**

TABLE 4.1. TEST FOR: (I) WAVELENGTH PLAN CORRESPONDING TO EACH CHANNEL, AND (II) INSERTION LOSSES (ILS)

Channel	Specified λ (nm)	Transmitted λ (nm)	TX Power (dBm)	Line-In to Drop			Line-In to Express-Out			Express-In to Line-Out			Add to Line-Out		
				Measured λ (nm)	Measured Power (dBm)	Insertion Loss(dB)	Measured λ (nm)	Measured Power (dBm)	Insertion Loss(dB)	Measured λ (nm)	Measured Power (dBm)	Insertion Loss(dB)	Measured λ (nm)	Measured Power (dBm)	Insertion Loss(dB)
1	1544.526	1544.53	-6.1	1544.550	-14.7	8.6	1544.550	-8.444	2.344	1544.54	-15.114	9.014	1544.60	-12.257	6.157
2	1545.322	1545.32	-6.1	1545.550	-14.5	8.4	1545.340	-8.51	2.41	1545.30	-15.366	9.266	1545.38	-11.8	5.7
3	1546.119	1546.12	-6.1	1546.150	-14.943	8.843	1546.140	-8.537	2.437	1546.14	-15.07	8.97	1546.16	-11.623	5.523
4	1546.917	1546.92	-6.1	1546.950	-15.7	9.6	1546.930	-8.544	2.444	1546.92	-15.35	9.25	1547.00	-11.774	5.674
5	1547.715	1547.72	-6.1	1547.750	-15	8.9	1547.730	-8.56	2.46	1547.70	-14.976	8.876	1547.78	[illegible]	[illegible]
6	1548.515	1548.52	-6.1	1548.540	-14.8	8.7	1548.520	-8.548	2.448	1548.52	-15.07	8.97	1548.58	-12.101	6.001
7	[illegible]	[illegible]	-6.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	1550.116	1550.12	-6.1	1550.170	-14.9	8.8	1550.130	-8.54	2.44	1550.12	-15.56	9.46	1550.21	-11.607	5.507
9	1550.918	1550.92	-6.1	1550.970	-14.9	8.8	1550.936	-8.75	2.65	1550.96	-15.713	9.613	1550.99	-12.23	6.13
10	1551.721	1551.72	-6.1	1551.770	-14.8	8.7	1551.752	-8.697	2.597	1551.74	-15.573	9.473	1551.79	-12.927	6.827
11	1552.524	1552.52	-6.1	1552.580	-15.18	9.08	1552.544	-8.707	2.607	1552.54	-15.376	9.276	1552.62	-11.605	5.505
12	1553.329	1553.33	-6.1	1553.390	-15.21	9.11	1553.352	-8.75	2.65	1553.34	-15.624	9.524	1553.44	-12.067	5.967
13	1554.134	1554.13	-6.1	1554.176	-15.27	9.17	1554.180	-8.708	2.608	1554.16	-15.266	9.166	1554.24	-12.646	6.546
14	1554.94	1554.94	-6.1	1555.000	-15.34	9.24	1555.000	-8.74	2.64	1554.99	-15.673	9.573	1555.04	-12.903	6.803
15	1555.747	1555.75	-6.1	1555.800	-15.47	9.37	1555.800	-8.762	2.662	1555.80	-15.655	9.555	1555.85	-12.834	6.734
16	1556.555	1556.56	-6.1	1556.616	-15.5	9.4	1556.620	-8.84	2.74	1556.60	-15.689	9.589	1556.67	-13.341	7.241
Average			*-6.1*			*8.97*			*2.54*			*9.29*			*6.08*
Maximum according to Spec Sheet						*9.00*			*3.00*			*10.00*			*6.00*

*** CRC wavelengths are channel 5, 7, 9, 11.* *Channel-8 is delivered from BERT* ***Average Wavelength Drift 0.045 nm***

*** Only Channels 5, 7, 9, and 11 contain embedded TAP MONITORS (5%)*

4.1.2. Results

Results obtained from Individual ROADM testing (Fig. 4.1) are presented in Tables 4.1 and 4.2. Table 4.1 verifies the wavelength plan and insertion losses at various paths of the iROADM™1600 ROADM module. It displays the measured wavelength with received optical power and insertion losses for every segment (e.g. Line-in to Express-out, Express-in to Line-out etc.) of the ROADM module for each transmitted channel and reveals the following important facts:

1) The average drifting of wavelengths as the channels pass through the ROADM module is less than 0.045 nm or, 5.635 GHz. There is no significant drifting of wavelengths (due to temperature) even though the testing had been running for several days.
2) The average insertion losses at Line-In to Express-Out (2.54 dB), and Express-In to Line-Out (9.29 dB) are less then their specified maximum values (3 dB and 10 dB respectively). Hence, the average power loss for an express channel will be less than 12dB.
3) The average insertion losses at the Drop and Add paths are almost the same as their maximum specified values (9 dB and 6 dB respectively).
4) As observed during measurements, only channels 5, 7, 9 and 11 (shaded) contain internal tap monitors (5%) that can be used to measure the power levels of the designated channels.
5) The adjacent channel crosstalk provided by the ROADM module is less than -23 dB as observed at the OSA. The crosstalk is mainly introduced by the internal AWGs although the internal 2x1 optical switches provide crosstalk less than -50 dB.

TABLE 4.2. TEST FOR INTERNAL VOA RANGE (0 DB -20 DB) Date: Dec. 14, 2005

Channel	*Express-In to Line-Out*											
	Measured λ (nm)	*VOA (dB)*	*Measured Power (dBm)*	*VOA set value (dB)*	*Measured Power (dBm)*	*Actual Loss in VOA (dB)*	*VOA set value (dB)*	*Measured Power (dBm)*	*Actual Loss in VOA (dB)*	*VOA set value (dB)*	*Measured Power (dBm)*	*Actual Loss in VOA (dB)*
1	1544.54	0	-15.114	5.00	-20.126	-5.01	15.00	-30.27	-15.16	20.00	-35.4	-20.29
2	1545.30	0	-15.366	5.00	-20.338	-4.97	15.00	-30.14	-14.77	20.00	-35.487	-20.12
3	1546.14	0	-15.07	5.00	-20.26	-5.19	15.00	-30.578	-15.51	20.00	-35.336	-20.27
4	1546.92	0	-15.35	5.00	-20.31	-4.96	15.00	-30.14	-14.79	20.00	-35.56	-20.21
5	1547.70	0	-14.976	5.00	[illegible]	-4.88	15.00	-30.53	-15.55	20.00	[illegible]	[illegible]
6	1548.52	0	-15.07	5.00	-20.112	-5.04	15.00	-29.68	-14.61	20.00	-35.12	-20.05
[illegible]	[illegible]	0	-15.176	5.00	[illegible]	[illegible]	15.00	-29.576	[illegible]	[illegible]	[illegible]	[illegible]
8	1550.12	0	-15.56	5.00	-20.6	-5.04	15.00	-29.74	-14.18	20.00	-35.48	-19.92
9	1550.96	0	-15.713	5.00	-20.65	-4.94	15.00	-30.53	-14.82	20.00	-35.48	-19.67
10	1551.74	0	-15.573	5.00	-20.68	-5.11	15.00	-30.538	-14.97	20.00	-35.4	-19.83
11	1552.54	0	-15.376	5.00	-20.41	-5.03	15.00	-30.707	-15.33	20.00	-35.48	-20.1
12	1553.34	0	-15.624	5.00	-20.58	-4.96	15.00	-30.656	-15.03	20.00	-35.47	-19.85
13	1554.16	0	-15.266	5.00	-20.32	-5.05	15.00	-30.37	-15.1	20.00	-35.552	-20.29
14	1554.99	0	-15.673	5.00	-20.64	-4.97	15.00	-30.207	-14.53	20.00	-35.49	-19.82
15	1555.80	0	-15.655	5.00	-20.72	-5.07	15.00	-30.456	-14.8	20.00	-35.38	-19.73
16	1556.60	0	-15.689	5.00	-20.71	-5.02	15.00	-30.747	-15.06	20.00	-35.28	-19.59
	Average					***-5.02***			***-14.91***			***-20***

***** All 16 channels contain internal VOAs (works almost linearly for 0dB - 20dB)***

Table 4.2 displays the attenuation capability of the internal VOAs embedded at each channel within the Express-In to Line-Out segment of the ROADM module. For every transmitted channel, the corresponding internal VOA is adjusted to a specific value and then the power of the attenuated optical signal is observed after the ROADM module to check whether the internal VOA works linearly. As depicted in Table 4.2, all the internal VOAs within the ROADM module work almost linearly within the specified range of 0 dB to 20 dB.

4.2. AON System Testbed

In order to experimentally validate our proposed design layout for reconfigurable All-Optical Network (AON) and also to verify the developed simulation models, an AON testbed has been designed and implemented using PLC-based ROADM module to be described in the following sub-section. The objectives of these experiments are to characterize the prototype reconfigurable element's performance in metro network environment and also to verify simulation models under similar scenarios so that the developed models can be used for future metro network designs.

4.2.1. Experimental Setup

Fig. 4.2. depicts the experimental setup implemented using the most advanced 16-channel PLC-ROADM module. Four channels of C-band: 1547.72 nm (Channel-5), 1549.32 nm (Channel-7), 1550.12 nm (Channel-8) and 1550.92 nm (Channel-9) are transmitted through the system and all are considered as express-channels in order to characterize the network parameters for the worst case scenario. Each wavelength is generated using a Transmitter

(Tx) with a power of -3 to -6 dBm and at a bit rate of 2.48 Gbps. The Txs use Non-Return-to-Zero (NRZ) pulses and Pseudo Random Bit Sequence (PRBS) of order 23 (i.e. 2^{23}-1).

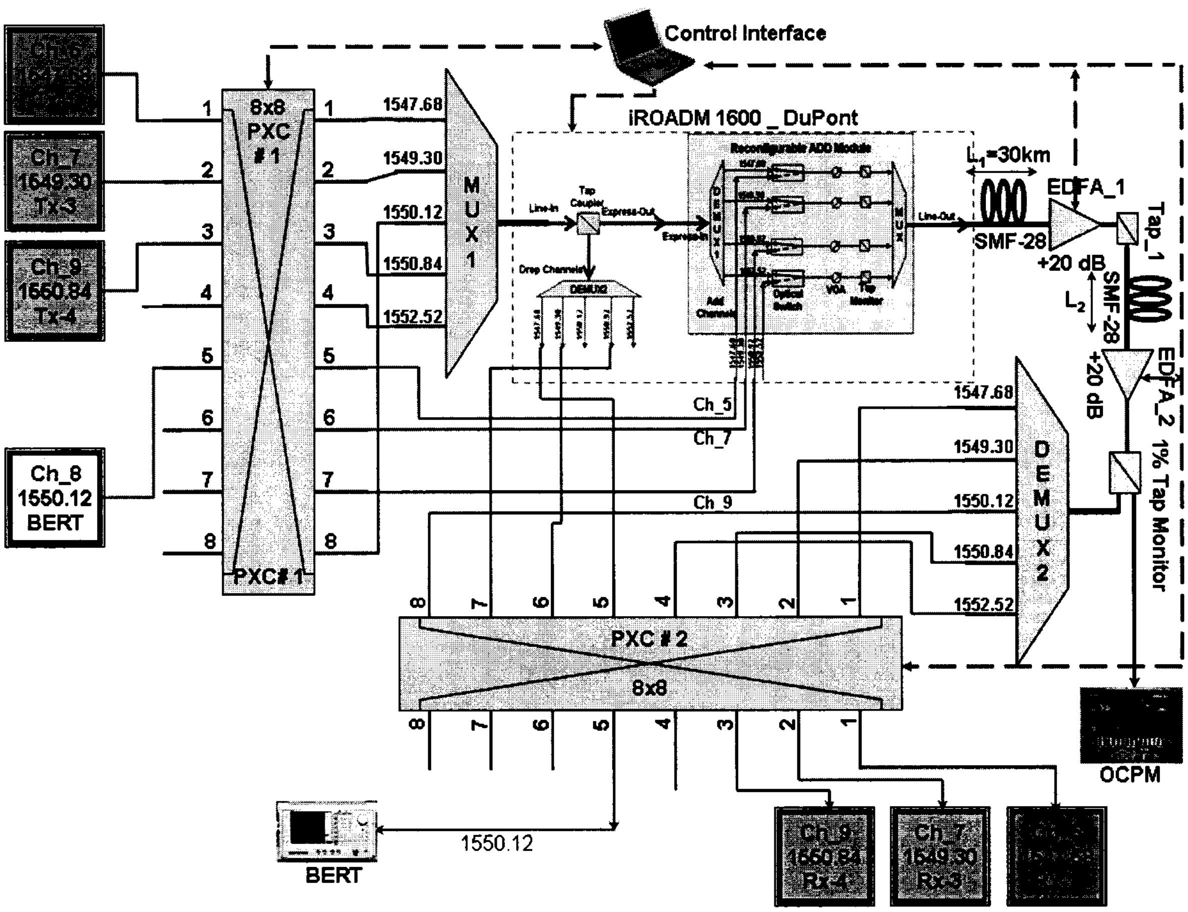


Fig. 4.2. Experimental setup in order to characterize the performance of a single node of the next generation metro network.

A MEMS-based *8x8* Photonic Cross-Connect (*PXC # 1*) is installed in the system only to add the flexibility of changing the express/add subsets, while *PXC # 2* provides the flexibility of receiving any channels from the drop/express subsets. Both PXCs have an insertion loss less than 3.7 dB and provide an adjacent channel crosstalk less than -50 dB. Two AWGs (*Mux 1* and *DeMux 2*) are setup in the testbed in order to provide a multiplexed input to the ROADM node and to extract express-channels at the receiving end respectively.

Both AWGs provide an adjacent channel crosstalk less than -23 dB with an insertion loss less than 3.5 dB. Thus, at the input of the ROADM node, the channels arrive with a power of -11 dBm to -14 dBm. The express-channels face a loss around 12 dB while passing through the ROADMs and internal VOAs are then required to be adjusted to equalize the power levels among all channels. Hence, all the four channels coming out of the ROADM module have a power level of around -26 dBm per channel (their combined output power is around -20 dBm).

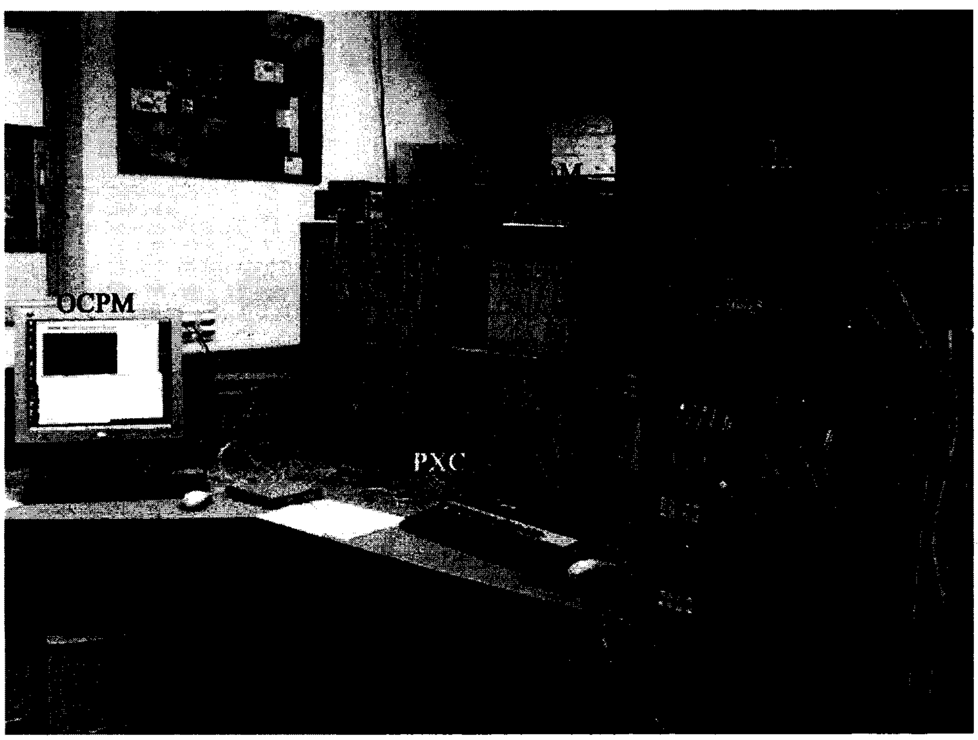


Fig. 4.3. Testbed implemented at the Broadband Applications and Optical Networking Lab in Communications Research Centre (CRC), Ottawa, ON, Canada [CRC06]

Single Mode Fibres (SMF-28) associated with EDFAs are installed just after the ROADM module. The SMF-28 fibres provide a loss around 0.2 dB/km, while the noise figure and the gain introduced by the EDFAs are not more than 6 dB and 20 dB respectively. Tap monitors (1%) are placed at desired locations as shown in Figure 4.2 to monitor the performance of the channels in terms of OSNR and optical power with the help of Optical Channel Performance Monitor (OCPM) [BaIn06]. Finally the demultiplexed channels are switched to a set of Receivers (Rxs) and a Bit Error Rate Tester (BERT) that provides the measurement of Bit Error Rate (BER) and eye diagrams for the *BERT Channel* (Channel-8 @1550.12 nm). A common control interface is developed in order to control the ROADM module, the gain of the EDFAs and the switching of the PXCs so that a single user can control the channels all over the network from a single point. A snapshot of the implemented testbed is presented in Fig. 4.3.

All the tests carried in the experimental testbed have been repeated in the simulation to be described and compared in the next sub-sections.

4.2.2. Simulation Model Verification

Simulation models have been developed for the AON testbed using the models described earlier in Chapter 3. The parameters for the ROADM model is reconfigured using the operational parameters obtained in Section 4.1. The developed simulation models are verified with experimental results under two scenarios. In the first scenario, we want to investigate where exactly the EDFA is required to be placed for the prototype ROADM module and how accurate the simulation models could predict such scenario. In the second scenario, a second EDFA is positioned at different distances and we want to investigate if my simulation models could effectively perform in case of cascaded EDFAs. Mean values of both Q-factor, and OSNR obtained from 4 simulation runs are presented in this thesis with 95% confidence interval. Examples are shown in Figs. 4.4 and 4.7. Since they are in general quite small, they will not be included in other future performance curves for clarity. The notations L_1 and L_2 indicate the locations of EDFAs as displayed in Fig. 4.2. As mentioned, the experiments have been done in two steps: in Step (1), only a single segment of fibre and an EDFA are installed to obtain the optimum length for L_1, while in Step (2), two fibre segments are installed with EDFAs to obtain the optimum length for L_2. Results obtained from both the steps are presented below:

Step (1):

In the first step, only a single fibre span of SMF-28 is laid between the ROADM node and the *EDFA_1* (Fig. 4.2). The *EDFA_1* is set to provide a gain of 20 dB and the amplified channels are then connected directly to the *Demux_2*. A tap-monitor (*Tap_1*) is placed just after EDFA_1 to monitor the OSNR and the optical power of the received channels. My objective is to obtain the optimum length of the fibre segment between the ROADM node and the *EDFA_1*.

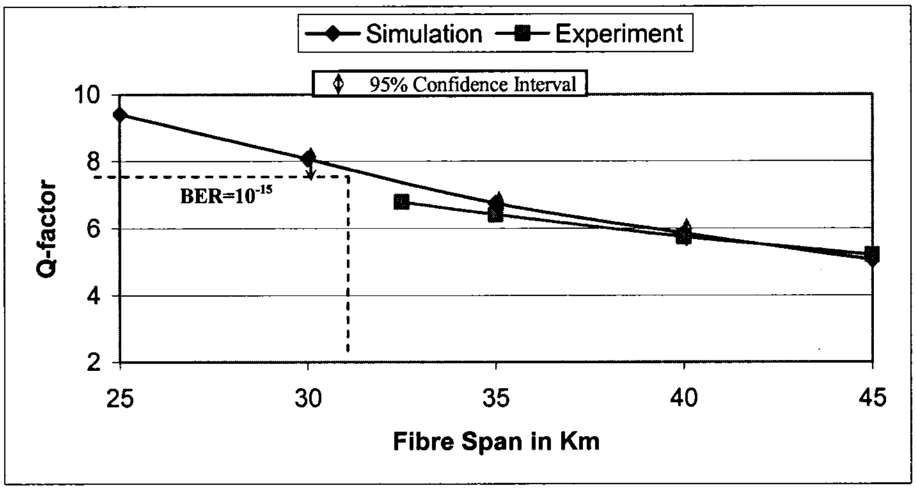


Fig. 4.4. Q-factor vs. the length of the fibre segment (L_1) beyond the ROADM node

Fig. 4.4 depicts the performance of Channel-8 (1550.12 nm) in terms of the Q-factor obtained at the receiving end from both simulation and measurements from the system testbed that also demonstrates the accuracy of the simulation models closely following the experimental results (within ±5%) over a broad range of fibre span. The 95% confidence interval for each of the simulation points is depicted in Fig. 4.4 that shows a very little variation (< ±0.3). Simulations have also been run for different values receiver's dark current (not shown) that is finally settled at 33.95 μA. As demonstrated in Fig. 4.4, the Q-factor of the signal goes down as low as 6.41 (BER ≈ $7x10^{-11}$) (measured from system) after traveling the maximum allowed distance of 35 km (Section 3.2, p. 35). However, in order to satisfy the latest Forward Error Correction (FEC) requirement [RhTo02], a fibre span of 30 km (≈ L_1) is allowed, after which the Q-factor of the signal becomes 7.6 (BER ≈ 10^{-14}, obtained from simulation). It should be noted that the BERT installed in the system does not display any error for a Q-factor more than 7.65 (BER ≈ 10^{-14}) as they cannot be measured.

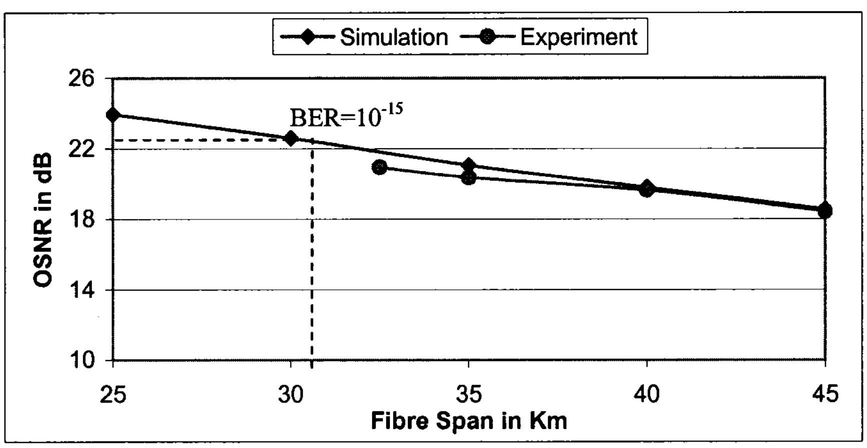


Fig. 4.5. OSNR of Channel-8 vs. the length of the fibre segment (L_1) between the ROADM node and the EDFA_1

The OSNR of Channel-8 obtained both from simulation and OCPM in the testbed are presented in Fig. 4.5. The simulation results closely follow the experimental results at the 95% confidence interval (equivalent to ±0.49 dB). The OSNR of the signal decreases almost linearly with the distance as expected. At the maximum fibre length of 35 km, the OSNR of the signal goes down at 20.6 dB (Fig. 4.5), while for the allowable distance of 30 km, the OSNR is around 22 dB.

A series of eye diagrams measured at the receiving end for different lengths of fibre segments are presented in Figs. 4.6a-4.6c. As the signal travels more and more distance through the fibres, the eye diagram performance becomes inferior as expected and consequently the value of Q-factor and the OSNR of the signal degrade.

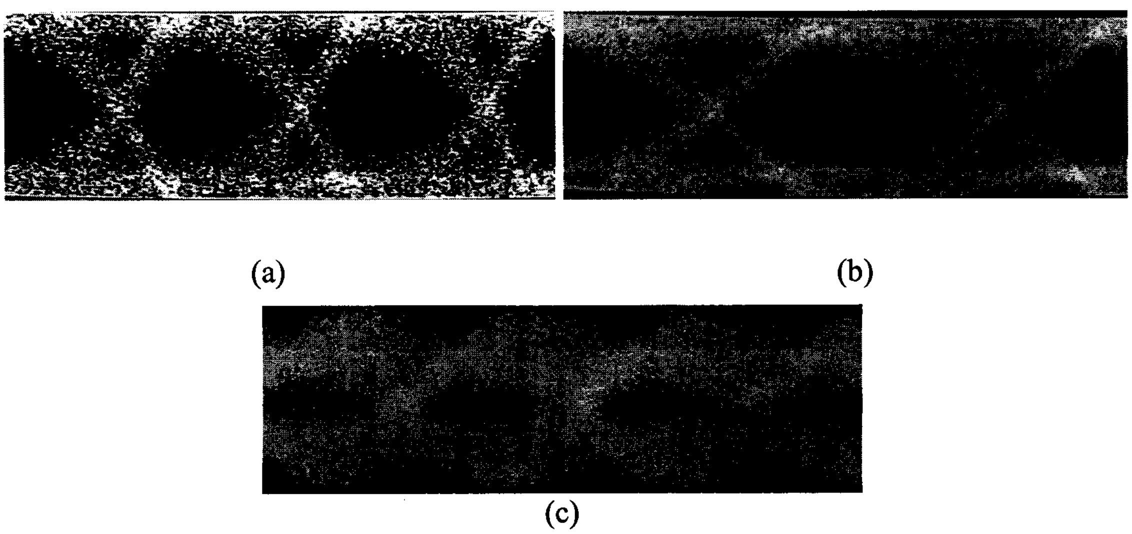


Fig. 4.6. Eye diagrams for Channel-8 at the position of Tap_1 for different lengths in the first fibre segment. (a) Fibre span = 1 km, BER =0.0, OSNR = 29.56 dB , (b) Fibre span = 32.5 km, BER = 5.2x 10^{-12}, OSNR = 20.95, (c) Fibre span = 45 km, BER = 9.75x 10^{-8}, OSNR = 18.43. Time scale: 200ps/div, Transmission speed: 2.48 Gbps.

Step (2):

In the second stage, a second set of fibre segment associated with *EDFA_2* is connected after *Tap_1* just as shown in Fig. 4.2. The length of the first fibre segment is set at 30 km, while both EDFAs are pumped so that each of them provides a gain of 20 dB. A tap monitor is placed just after *EDFA_2* in order to monitor the channels' OSNR.

As discussed in Chapter 3, the maximum possible length of the second stage of fibre segment can be 100 km mainly based on the gain of the corresponding EDFA (20 dB) in the system. However, in reality the possible span of fibre that can be deployed at the second stage is much lesser than its maximum value. As shown in Fig. 4.7, the optical signal can travel as far as 60 km in the system testbed while still maintaining a satisfactorily good quality with Q-factor at 6.7 (BER $\approx 10^{-11}$).

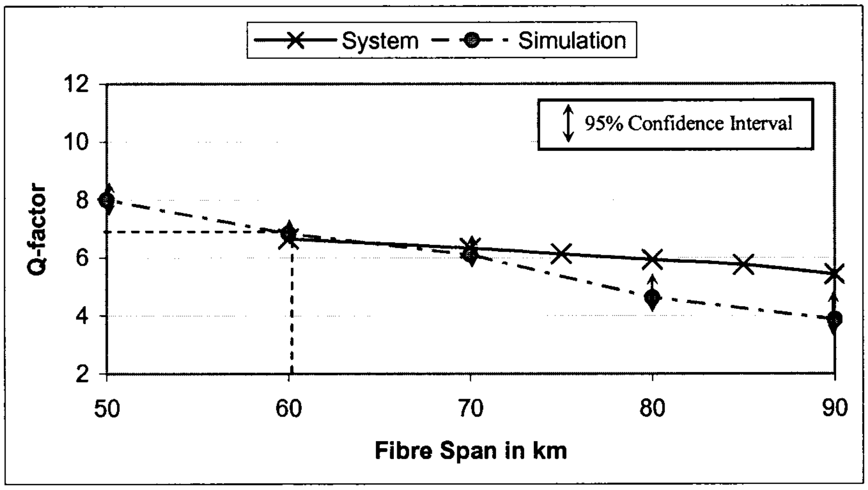


Fig. 4.7. Q-factor of Channel-8 as it travels through the second stage of fibre segments (L_2) associated with EDFAs

However, Fig. 4.7 depicts that the obtained simulation results show more variation than the system measurements. Their difference is small (within the range of ±7%) up to a distance of 75 km at the second stage (BER $\approx 10^{-9}$). Note that the simulation results may not be so reliable here for very low values of Q-factor (e.g. $Q < 5.0$; BER $> 10^{-6}$) since the Gaussian approximation method used in the BERT of the simulation model fails to predict the actual value if the received optical signal is very weak. This is evident from the large percentage of error as depicted in Fig. 4.7 beyond the distance of 75 km. Hence, based on the above measurements, 60 km of fibre span ($\approx L_2$) is preferred for the second stage. At this point the signal still shows a good quality even if its performance is slightly lower than the latest FEC requirement.

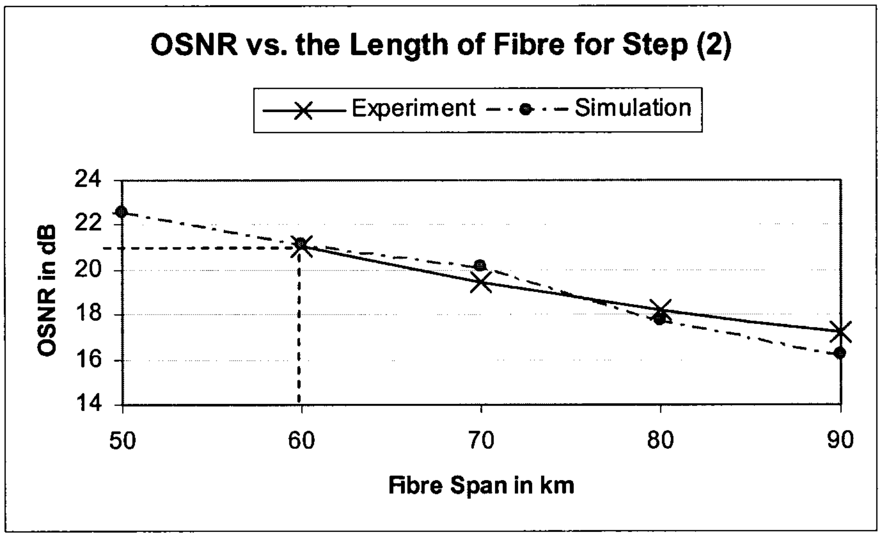


Fig. 4.8. OSNR of Channel-8 measured after EDFA_2 as the signals travel through the second segment of fibre span

The variation in OSNR for the signal at the second stage obtained from the system testbed (OCPM) is depicted in Fig. 4.8. The simulation results for OSNR also show a similar degradation with the increase in the fibre span, and its variation with the experimental measurements is less than ± 6% (< 1 dB). However, for the distance of 60 km at the second stage, the signal maintains a good OSNR (21 dB) as suggested, both by the simulation and the testbed results.

The above experiments can be conducted for multiple stages of EDFA placements. However, in the measurements and simulations only metro network scenarios are considered. For a long haul network, after the second stage, it would be a general fibre and EDFA placement problem. Equipped only with EDFAs, a signal can travel as long as 264 km (BER $\approx 10^{-9}$) without regeneration at a transmission speed of 5 Gbps as reported by [BeDa95].

4.3. Concluding Remarks

In this chapter, several test-beds have been developed and demonstrated in order to characterize the different parameters of one of the most advanced prototype ROADM module and also to experimentally validate its performance in metro network environment according to my proposed design layout for next generation network (Chapter 3). Simulation models have also been developed and their performances have been compared with the real system measurements. The results presented in this chapter validate the developed simulation models that can predict real modules' behavior as well as overall system's performance over broad range of fibre span with an acceptable accuracy. The worst case performance of simulation models occur for predicting the OSNR for 2nd stage that arrives with a variation of ±1 dB. However, it should be noted that even in the experimental measurements, the real-time OSNR (measured by OCPM) keeps changing its values by ±0.5 dB. Hence a ±1 dB variation between the simulation results and experiments is quite acceptable as long as the signal's OSNR remains considerably high. However, all the simulation and experimental results presented in this chapter have been obtained at a bit rate of 2.48 Gbps and maintained the latest FEC requirement (BER $\approx 10^{-15}$).

These verified simulation models can definitely be used for further research on improving the design and the architecture for next generation network with ROADMs with an acceptable accuracy without buying those expensive optical equipments. A few examples of these next generation architectures developed with simulation models will be discussed in detail in Chapter 5.

CHAPTER 5: NEXT GENERATION ARCHITECTURE WITH ROADMS

This chapter concentrates on developing a low-loss architecture for ROADM subsystems. It proposes detailed design lay-outs for interconnections among different ring networks in optical domain realized by using PLC-based ROADMs for the first time. A proposal is made to introduce some level of intelligence to these 3rd generation ROADM modules that would be able to balance the power levels dynamically among the existing express- and add-channels. Architectures and results presented in this chapter are based on the simulation models verified in previous chapter.

5.1. Hybrid Low-Loss Architecture for ROADMs

Although PLC-based ROADMs have become popular, the major drawbacks are their high insertion losses, especially for express channels (10 dB to 13 dB) [JPLC06], [DuPo05], while all ports in their drop and add modules are wavelength specific (colored ports). This later feature of colored ports imposes the biggest limitation on PLC-based ROADM module where customers always need to be connected between themselves by specific channels.

Wavelength Selective Switch (WSS)-based ROADM [JWSS06, WsMe05] is one of the most recently introduced architectures. However, in order to build a colorless ROADM subsystem two WSS modules [JWSS06, WsMe05] are required – one for the add and another for the drop functions [Metc05a]. Although a single WSS imposes low insertion loss (to 5.5 dB) for express channels, the combination of two WSS modules increases this loss to at least 11 dB [WsMe05]. The WSS module also integrates more devices than its PLC counterpart and the integration of all of its lightpaths over the Silicon-wafer makes the ROADM subsystem more costly than any other structures. This is to note that there is a recent patent [DyWa05] available on WSS module that could do both add and drop within the same module, but no other relevant information (e.g. loss, cost, availability etc.) is available regarding this module. The WSS module referred and compared in this thesis is available at [WsMe05] for which I had the access to review its spec-sheet.

Hence, between the two most popular ROADM subsystems, the PLC concentrates only on simpler manufacturing approach having colored ports and reduced costs, while WSS-based ROADM concentrates only on having colorless ports irrespective of cost and manufacturing constraints. In this section, I present a hybrid architecture for ROADM subsystems that combines the best features of both PLC and WSS technology. The proposed Hybrid-ROADM architecture provides less loss than the other existing structures and also affords the advantage of having colorless connectivity. A metro network testbed is designed and simulated to characterize the performance of the proposed hybrid design and is compared with the performance of the latest PLC- and WSS-based ROADM subsystems.

The next few sub-sections first describe the proposed hybrid architecture for ROADM subsystem and then demonstrate its comparison with the other latest ROADM architectures in terms of network integration and characterization of design parameters.

5.1.1. The Hybrid Architecture

Fig. 5.1 shows the internal structure of the proposed hybrid architecture for an *N*-channel ROADM subsystem. The Hybrid architecture contains a monitored demultiplexer (*DeMux 1*) for wavelength specific drop ports (for all *N* channels) followed by a Wavelength Selective Switch (WSS) module that provides the features of *(M-1)* number of colorless add ports. The functional technologies of the proposed Hybrid architecture depends on the integration of AWGs, couplers, optical switches, VOAs, and tap monitors for monitoring optical power in desired locations. The ROADM module contains *Mx1* optical switches that can be manufactured using MEMS technology, while the rest of the devices can be developed using PLC technology.

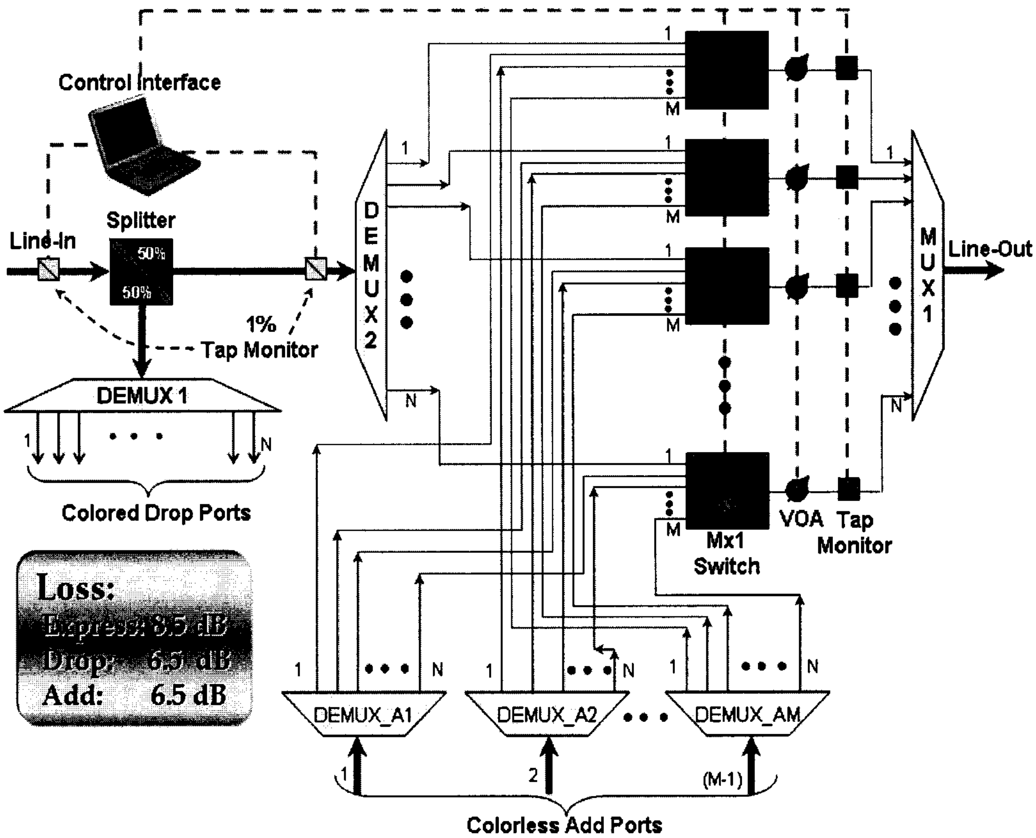


Fig. 5.1. Proposed architecture for Hybrid-ROADM module

The incoming optical signals are usually brought to the *Line-In* input port. A fraction of the input is diverted towards *DeMux 1* that basically acts as a receiving demultiplexer to *drop* the received channels. The rest of the input is carried towards *DeMux 2* that separates them into *N* number of channels. Each channel contains an *Mx1* MEMS switch that provides very low loss hitless switching followed by a VOA and a tap monitor for power adjustment purposes. Each add-port is connected with an AWG that provides the connectivity with all channel specific switches and makes the designated add-port virtually colorless. The *Mx1* switches select either the *express* channel, or any of the *add* channels for their output. Finally the express-channels and the newly added channels (if any) come directly to the output through the *Line-Out* output port.

A common control interface is developed for the Hybrid-ROADM architecture that provides the control over the *Mx1* MEMS switches and VOAs placed within the add module. It can also be used to monitor the power level of different channels by placing tap monitors on desired locations. With the help of VOAs and internal tap monitors, it is possible to develop a dynamic power balancing system that will equalize the power levels between different express- and add-channels in order to avoid anomalies in designing network parameters.

Since the optical paths of both the WSS and AWGs are always reversible, the low-loss Hybrid structure for ROADM subsystem can also be developed using the WSS as a reconfigurable drop module followed by a monitored multiplexer for add module as shown in Fig. 5.2.

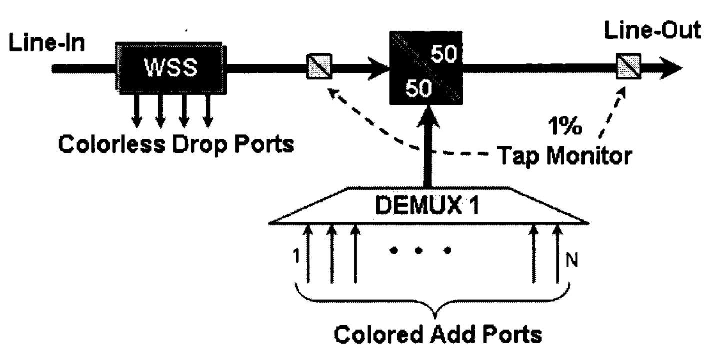


Fig. 5.2. The alternative architecture for Hybrid ROADM subsystem

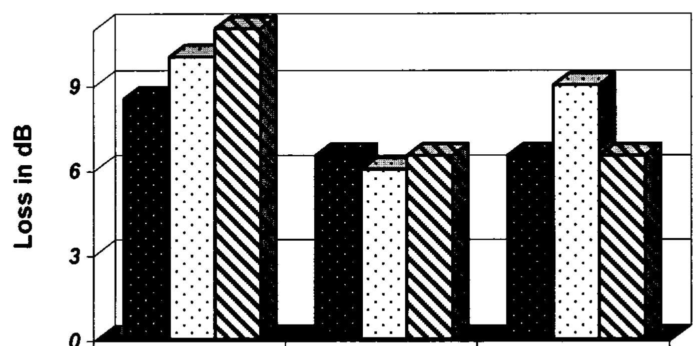
Service providers can choose any of these two proposed models (either Fig. 5.1 or 5.2) depending on the type of their application and network requirement. However, for the rest of this section, only the hybrid structure proposed in Fig. 5.1 is considered in order to compare its performance with other existing ROADM subsystems.

5.1.2. Comparison with other Architectures

The performance of the proposed Hybrid-ROADM architecture is compared with the PLC- and WSS-based ROADM [WsMe05] subsystems in terms of insertion losses, and operational flexibility and costs.

5.1.2.1. Insertion Loss

For the hybrid structure shown in Fig. 5.1, the integrated WSS module provides a loss around 5.5 dB for express-channels, while for add-channels the loss is around 6.5 dB. A splitter is being used to split the power into half (3 dB loss), thus making the total loss for express-channels as 8.5 dB. The AWG (*DeMux 1*) at the drop module provides a maximum insertion loss of 3.5 dB that makes the total loss for drop channels as 6.5 dB.



	Express	Add	Drop
■ Hybrid-ROADM	8.5	6.5	6.5
□ PLC-ROADM [DuPo05]	10	6	9
▧ WSS-ROADM [WsMe05]	11	6.5	6.5

Fig. 5.3. Loss comparison among different ROADM architectures

A comparison with other structures in terms of insertion losses is shown in Fig. 5.3. The proposed Hybrid architecture certainly provides lower loss for express-channels, while for add-/drop-channels the insertion losses are the same as the WSS-based ROADM subsystem [WsMe05]. However, instead of using the 50% splitter, it is possible to use a splitter with different power ratios depending on the type of application for which the ROADM will be used. For example, a 30%/70% splitter can be installed that will divert 70% of the total power towards the reconfigurable add module. In such case, the loss for express channels will be around 7 dB, while for drop channels the loss will be increased to 8.7 dB.

5.1.2.2. Operational Flexibility and Cost

Although the proposed Hybrid-ROADM architecture increases the design complexity and manufacturing cost as compared to the PLC-ROADM, it certainly introduces the advantage of having colorless add-, or drop-ports. Such hybrid design will be suitable and cost-effective for a network having high channel count applications (16-80 channels). With PLC-ROADM, fibre connections are always port-specific that ultimately increases the OPEX for the overall network. However, with the proposed Hybrid-ROADM structure (shown in Fig. 5.1), service providers would now be able to transmit a number of wavelengths through a single colorless add port. Hence, the proposed design will definitely reduce the total number of ports in the network and thus the overall network operating costs (OPEX).

Unlikely the WSS-based colorless ROADM subsystem [WsMe05], the proposed hybrid architecture will definitely reduce the cost almost by half in every aspect as it integrates only a single WSS with an AWG with reduced loss and design complexity. However, the hybrid design loses the flexibility of having *All-Colorless* ports as compared to the WSS-based ROADMs [JWSS06, WsMe05].

5.1.3. Network Integration and Comparison

Although the conventional idea is to mount optical amplifiers with ROADM modules [RhTo03, SoCh03, BoSh02, LiLi02, RhTo02] as shown earlier in Fig. 2.1 (Chapter 2), the low-loss feature of the proposed hybrid structure will alleviate the requirement of mounting optical amplifiers with the ROADM module that will be demonstrated in the next sub-section.

5.1.3.1. System Setup

In order to characterize the performance of our proposed Hybrid-ROADM subsystem in metro network environment and compare its performance with PLC- and WSS-based ROADMs, simulation-models have been developed for PLC- [DuPo05] and WSS-based ROADM [WsMe05] subsystems according to their available spec-sheet, and also for a 5-channel Hybrid-ROADM subsystem with 4 colorless add-ports. The adjacent channel isolation provided by the Hybrid module is less than -20 dB (mainly influenced by the AWGs). The performance of the ROADM modules is compared by placing them in the testbed that has been demonstrated earlier in Chapter 4. The simulations are done initially with the Hybrid-ROADM module (shown by the dotted box in Fig. 5.4) and then it is replaced by the PLC- and WSS-based ROADM subsystems respectively. Five channels of C-band (Channels 5, 7, 8, 9, and 11) have been transmitted again through the system, and all are considered as express-channels in order to characterize the modules' performance for the worst case scenario. Each wavelength is transmitted at a bit rate of 2.48 Gbps and the characteristics of other optical equipments remain exactly the same as described earlier in Section 4.2. The simulation environments for all the setups are conducted according to the environment described at Section 3.4.1 and also following the same parameters as described in Appendix B except for those under investigation here.

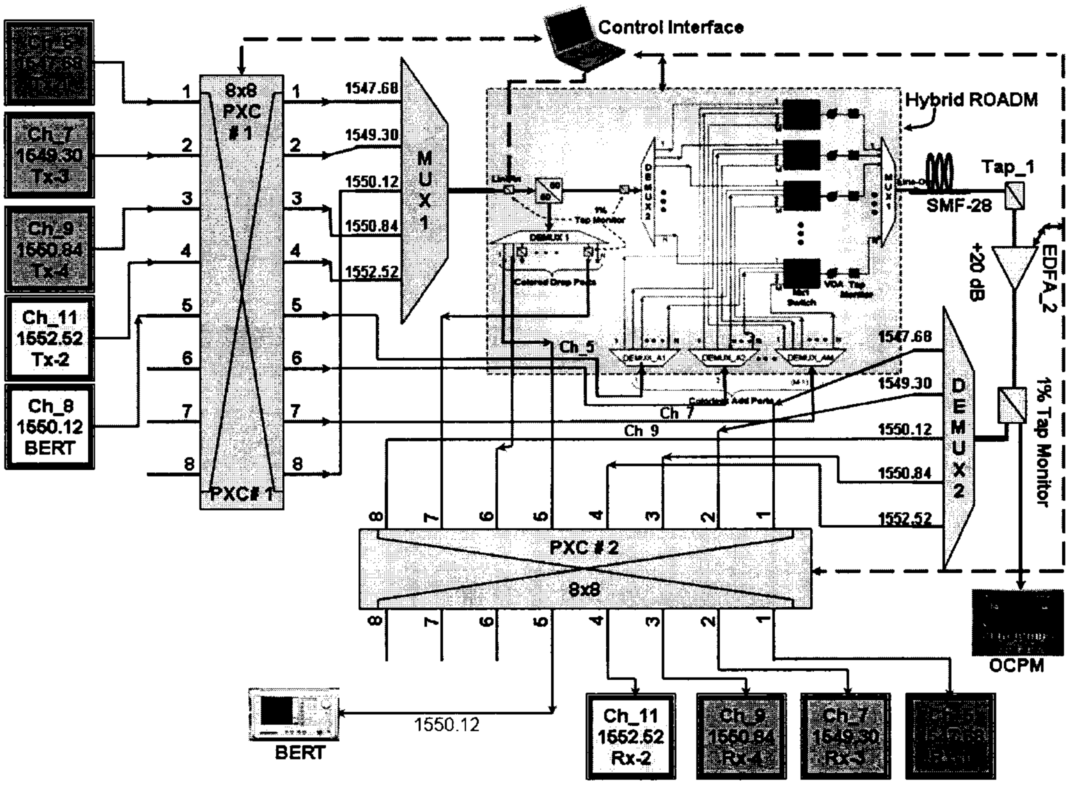
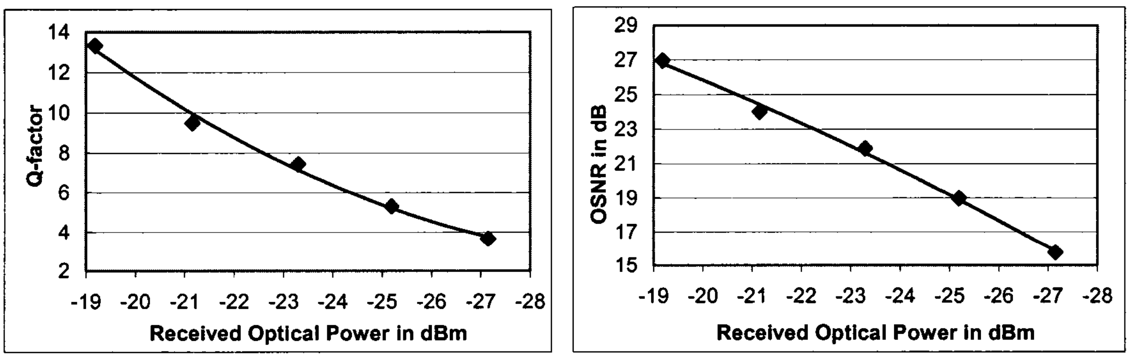


Fig. 5.4. Testbed to characterize the performance of Hybrid-ROADM architecture in metro network environment

5.1.3.2. Performance Comparison



(a) (b)

Fig. 5.5. Performance of Hybrid ROADM in terms of (a) Q-factor, (b) OSNR vs. received optical power

Fig. 5.5 depicts the best-fit curve (with 2nd order polynomial) for the simulation results obtained for the hybrid ROADM subsystem in the previously explained metro network environment as the optical signals travel through the various length of SMF-28 fibres installed just after the ROADM module. Their performance is recorded at 2.48 Gbps in terms of the optical power received at the end (at receivers). As displayed, the performance (both Q-factor and OSNR) of the express-channel reduces with the decrease in the optical power, and hence for travelling more fibre span.

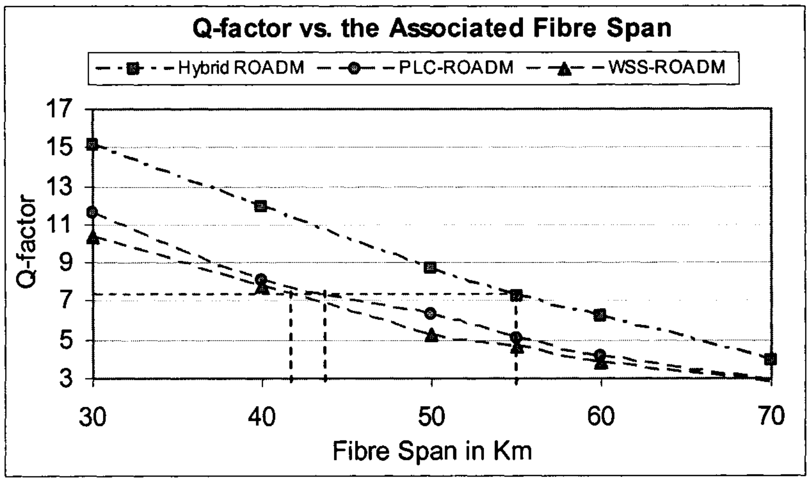


Fig. 5.6. Performance comparison among the ROADM architectures in terms of Q-factor vs. the associated fibre span

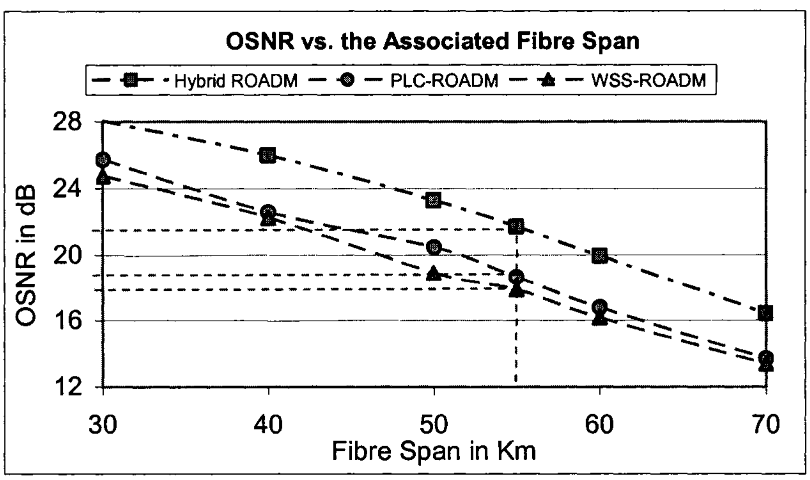


Fig. 5.7. OSNR vs. the associated fibre span for different ROADM architectures

Figs. 5.6 and 5.7 compare the performance of the optical signals for various ROADM modules in terms of the associated fibre span. The performance (both the Q-factor and OSNR) for the hybrid ROADM degrades with the increase in fibre span and the other ROADMs show similar characteristics. As shown in Fig. 5.6, the optical signals coming out of the Hybrid-ROADM module is strong enough to travel a significant amount of distance (55 km) before placing the first EDFA. At this point, the Q-factor of the received signal is 7.28 (BER $\approx 10^{-13}$) that is slightly less than the latest FEC requirement. However, to keep the same level of Q-factor ($\approx$ 7.28) with the PLC- and WSS-based ROADM modules, the maximum possible fibre span is around 40 km as evident from Fig. 5.6.

The Hybrid-ROADM module also maintains a good OSNR level for optical signals even after travelling 55 km (to 22 dB as shown in Fig. 5.7) that is much better than the PLC- and WSS-based ROADMs' performance (to 18 dB). After the first stage of fibre span and EDFA, it is a general EDFA placement problem [BeDa95].

5.2. Transparent Ring-to-Ring Interconnection

In this section, features are presented for developing interconnection between two metro ring networks in optical domain realized by using PLC-based ROADMs. The next few sub-sections demonstrate the proposed ring-to-ring interconnection with optimizing the performance of PLC-ROADMs in metro ring network in terms of associated fibre span and cascadability at 10 Gbps.

5.2.1. The Proposed Ring-to-Ring Interconnection

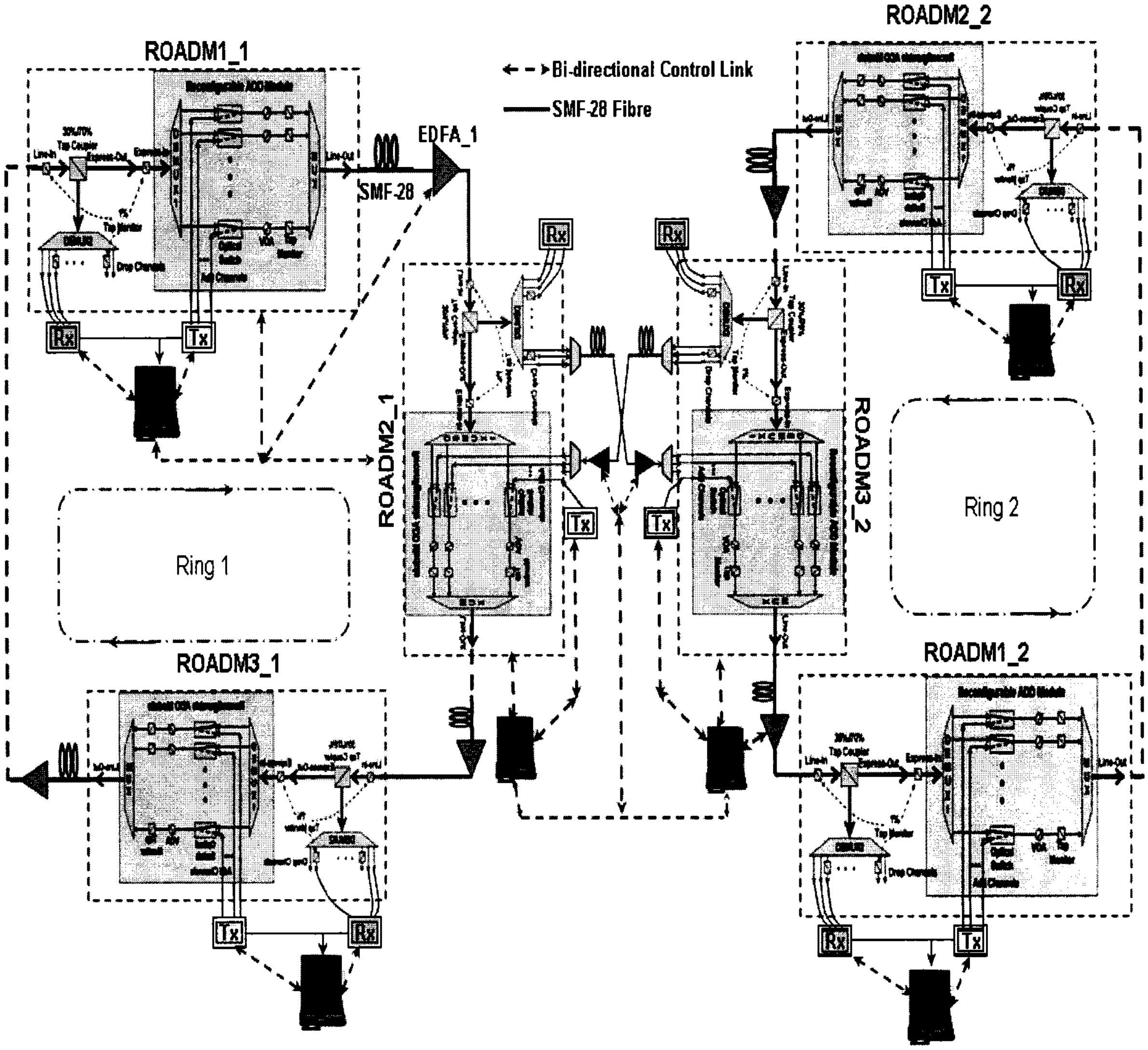


Fig. 5.8. Detailed Ring-to-Ring interconnection using PLC-based ROADM subsystems

Fig. 5.8 shows the detailed ring-to-ring interconnection feature using PLC-based ROADMs. This is a setup with two unidirectional ring networks with three ROADM nodes in each ring. No failure scenario is considered for simplicity of illustration as each ROADM node usually comes with east-west separation that ensures 1+1 protection. Single Mode Fibres (SMFs) are deployed between the ROADM nodes and each span of fibres are accompanied by EDFAs. One of the most basic advantages of using ROADMs is that there is no need for additional multiplexers/demultiplexers, or OXCs for the nodes anymore. Carriers can use ROADMs' add-ports to transmit new wavelengths, while those drop-ports can be used to see the received channels. However, the express channels of a ROADM node can be used for connecting with other nodes within the same ring. For interconnection between two rings, there are two possible scenarios:

1) *Fully Dedicated ROADM with Dynamic Channel Assignment:* One particular ROADM in each ring has to be dedicated for interconnection only. As shown in Fig. 5.8, all the four drop channels of ROADM 2 of Ring 1 (ROADM2_1) are connected to the four add ports of ROADM 3 of Ring 2 (ROADM3_2) through MUXs and DEMUXs and vice versa. Any of the four channels can be used for inter-communications provided that the status of that channel remains available for both rings during the period of communication. For example, if a client at ROADM1_1 intends to communicate with someone at ROADM2_2, he/she will first look for free channels available at both rings. Say, the client finds Channel-2 (λ_2) in this case while at the same time, another client at ROADM3_1 will be able to communicate with someone at ROADM1_2 using Channel-1 (λ_1) provided that λ_1 is also available for both rings. For a larger number of channels, a band of wavelengths can be used for communication between two rings while other bands can be specified for communicating with other rings.

2) *Partially Dedicated ROADM with Fixed Channel Assignment:* A ROADM node needs not to be dedicated for inter-communication only. Rather, only one particular channel can be made dedicated for interconnection. In such case, only one channel of ROADM2_1 (Fig. 5.8) needs to be connected to ROADM3_2 and vice versa, while the rest three can

be used either for launching new channels, or for communicating with the other neighboring rings. Each ROADM node needs to know the designated channel and the corresponding ring network for which the channel is specified. For example, λ_2 can be specified for interconnection between Rings 1 and 2, while λ_3 can be chosen for interconnection between Rings 1 and some other metro ring network (not shown in Fig. 5.8).

Service providers can follow any of the procedures described above although both of them come with their relative trade-offs. A fully dedicated ROADM, described in Scenario 1, will definitely raise the cost for initial installation and maintenance, but will add more reconfigurability and dynamic channel assignment for interconnecting metro ring networks. However, using a single channel in Scenario 2 will definitely lower the cost, but one channel needs to be kept dedicated for interconnection with each ring. Therefore, when there will be no data to send to other rings, those dedicated channels will remain under-utilized although they may be used for carrying some low priority traffics at that time.

5.2.2. Performance Optimization

The performance of a PLC-based ROADM in a metro ring network can be optimized in terms of two parameters: associable maximum fibre span and cascadability[9] of the ROADM module. The optimum length of the fibre segment that can be installed with the ROADM module depends on the number of channels and the type of the network, and obviously the characteristics of the optical amplifiers within the network. Network architectures with detailed experimental and simulation results have been demonstrated earlier in Chapter 4 that

[9] Cascadability defines the maximum number of a particular module that can be cascaded without regenerating the optical signal passing though the modules.

describe the possible length and the type of the fibre span that can be associated with the ROADM module in a metro ring network. However, it is also important to know how many PLC-based ROADMs can be cascaded in a metro ring network, or the maximum number of ROADMs that an optical signal can pass through in the case of ring-to-ring interconnection. The detailed of this cascadability feature for PLC-based ROADMs is described in the following sub-section.

5.2.2.1. Cascadability of PLC-based ROADM

In order to obtain the cascadability, a loop-test experiment has been simulated according to the setup shown in Fig. 5.9. EDFAs are connected just after the ROADM module that make sure to pump enough gain in order to compensate the total losses experienced by the channels while passing through the ROADM module. The characteristics of all optical components in the setup remain exactly the same as explained earlier in Section 4.2.1 following the simulation environment described in Section 3.4.1.

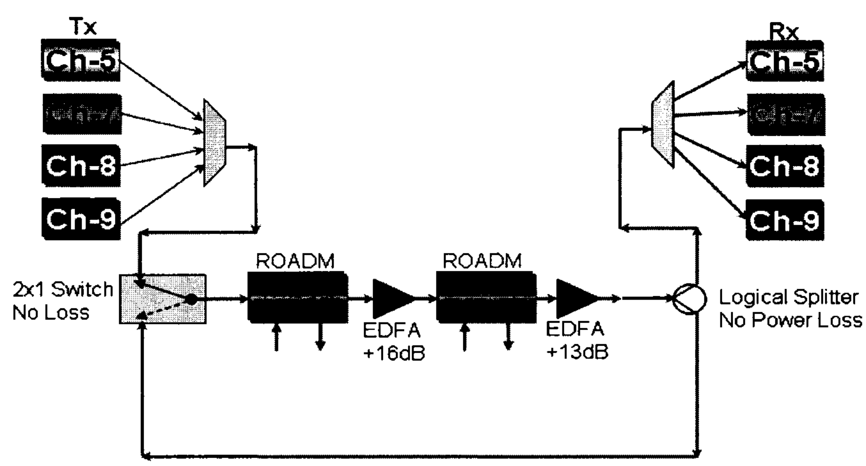
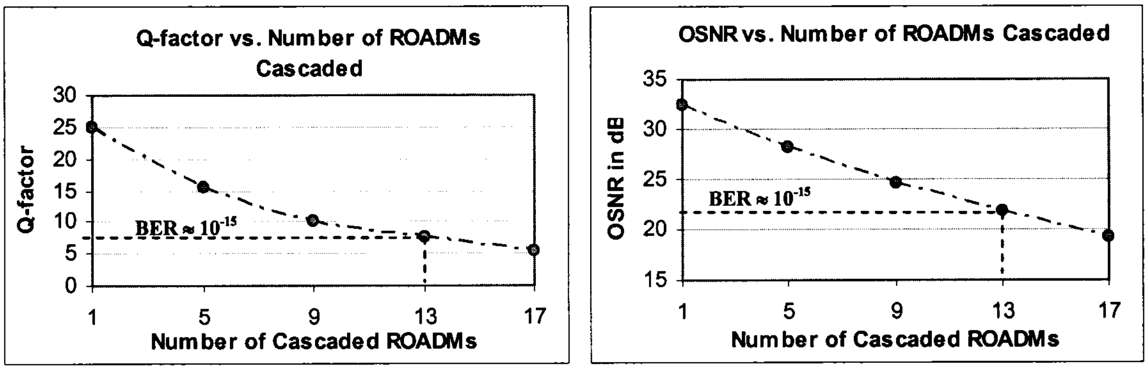


Fig. 5.9. Loop test conducted in simulation



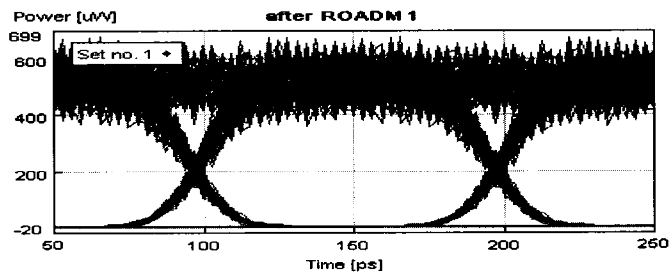
(a) (b)

Fig. 5.10. Performance in terms of (a) Q-factor, (b) OSNR with the number of cascaded ROADMs.

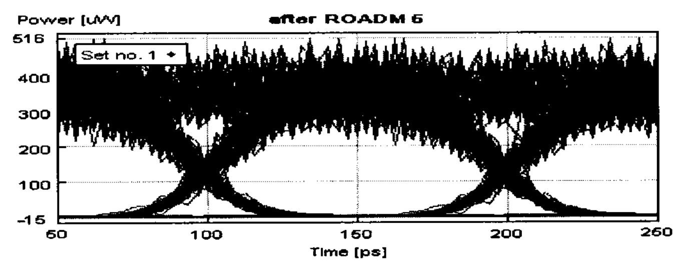
As shown in Fig. 5.9, the first EDFA provides enough gain to cover the losses of the first AWG and the 1st ROADM, while the second EDFA covers the losses experienced only trough the 2nd ROADM module. Logical splitters and switch have been used in the simulations that do not conduct any more losses to the optical signals. Four channels (Channels 5, 7, 8 and 9) are transmitted (expressed) at 10 Gbps and only the performance of Channel-8 is monitored in the simulation in terms of Q-factor and OSNR as depicted in Figs. 5.10a-5.10b.

As shown in Fig. 5.10a, the Q-factor for Channel-8 can go as low as 6.0 (BER $\approx 10^{-9}$) after passing through 16 PLC-ROADMs. However, in order to maintain the FEC requirement (BER $\approx 10^{-15}$), a maximum of 13 PLC-based ROADM modules can be cascaded at 10 Gbps. The OSNR of the channel also remains at a very good level ($\approx$ 22 dB) after 13 cascaded ROADM subsystems (depicted in Fig 5.10b). This is lower than the cascadability of WSS modules (stated as 32 at 10 Gbps by [WsMe05]). However, in practice, two WSS modules [JWSS06, WsMe05] are required to build a ROADM subsystem – one for the drop and the other for the add module respectively. According to this construction, the cascadability of

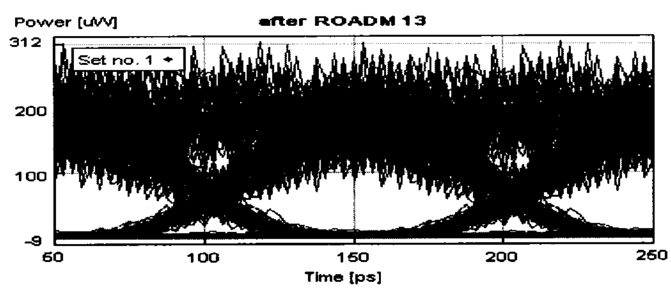
WSS-based ROADM subsystems will be 16. To the best of my knowledge, the vendor in [WsMe05] also does not mention whether the system performance maintains FEC requirement (BER ≈ 10^{-15}) after those 32 cascaded WSS modules.



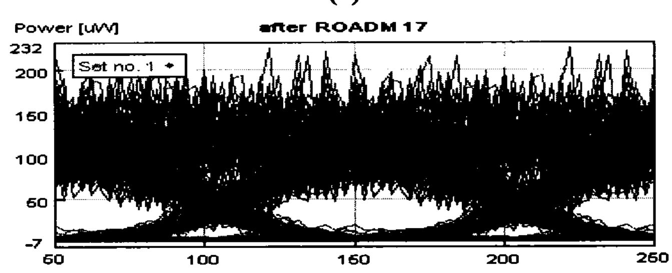
(a)



(b)



(c)



(d)

Fig. 5.11. Eye diagrams for Channel-8 obtained at bit rate 10 Gbps (a) just after the first ROADM, Q-factor = 24 (b) after passing through 5 ROADMs, Q-factor = 15.4 (BER ≈ 10^{-49}), (c) after 13 ROADMs, Q-factor = 7.43 (BER ≈ 10^{-14}), (d) after 17 ROADMs, Q-factor = 5.4 (BER ≈ 10^{-8})

A number of eye diagrams for Channel-8 are shown in Figs. 5.11a-5.11d, obtained at different locations during transmission. The eye diagram performance becomes inferior, and consequently the value of Q-factor decreases as the optical signal passes through more and more ROADMs. Hence, based on the simulation results, it can be concluded that the cascadability of such PLC-based ROADM module is 13 at 10 Gbps. All of my proposals and simulations certainly maintain the latest FEC requirement.

5.3. Intelligent ROADM (I-ROADM) Subsystems

As mentioned earlier, the 3rd generation PLC-ROADM modules usually provide more losses for express-channels than that for add- and drop-channels. Hence, in next-generation metro optical network with multiple adding and dropping of channels, there will be a huge difference in the optical power levels among different channels. Such an irregular optical power level will create lot of anomalies to network designers, especially on selecting different network equipments e.g. optical amplifiers, and also make problems for low powered channels because of the effect of crosstalk and other nonlinear issues. Hence, in order to avoid such problems, the control of the ROADM subsystem can be updated to introduce some level of intelligence in order to develop an Intelligent ROADM (I-ROADM) module. We introduce some of the design concepts as follows.

The developed I-ROADM would be able to dynamically balance the optical power levels among all express- and add-channels. Usually the GUI of the ROADM node provides a level of control over its internal *2*x*1* optical switches, VOAs and tap monitors placed within the add module. With the help of these VOAs and internal tap monitors, it is possible to develop a dynamic power balancing system by writing the following pseudo-code over the ROADM's GUI:

```
Check    the power level of each channel using the internal Tap Monitors
Obtain   the lowest power level, Pmin (dBm)
Execute  command to adjust the internal VOAs of each channel attenuating
         by (Pn - Pmin) dB; n = 1, 2, ... ..., N
```

where N is the total number of channels. With the help of these pseudo-codes, the I-ROADM will always make sure that all the channels will have the same optical power levels that will eventually reduce the effect of crosstalk and other non-linear issues. Instead of developing I-ROADMs, it is also possible to adjust the internal VOAs manually to balance the power levels, and it would not be a big hazard if the number of channels are low (e.g. 4 or 5). However, consider a metro network scenario that may contain 32 channels or more where wavelengths will be added/dropped dynamically, then one will see the importance of developing I-ROADMs in order to balance the power levels for all 32 channels.

5.3.1. Performance demonstration of I-ROADM

In order to demonstrate the advantage of the power-balancing feature of I-ROADMs, a metro network testbed has been designed and simulated as shown in Fig. 5.11.

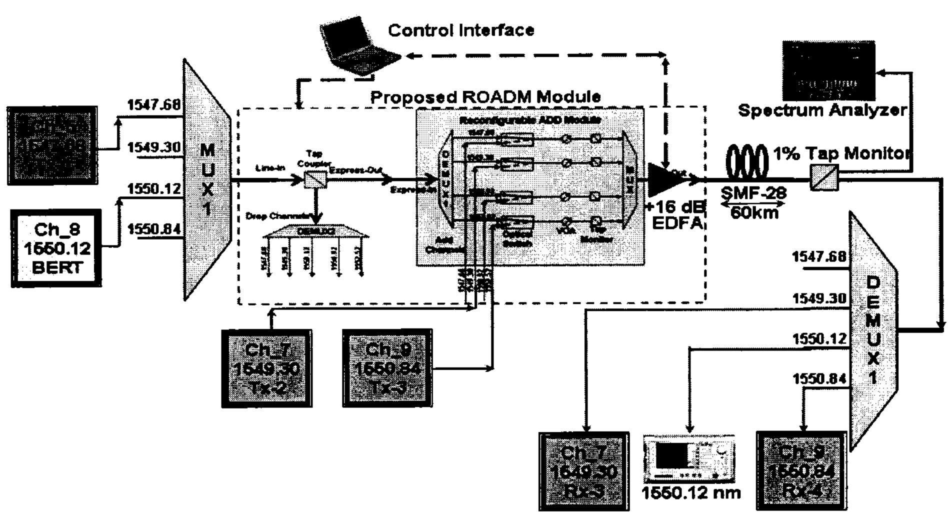


Fig. 5.11. Testbed to demonstrate I-ROADM's performance

VPItransmissionMaker [VPIP06] simulation tool has been used to develop simulation models for the I-ROADM module that is basically the same as the PLC-ROADM module with the capability of providing dynamic power balancing features. In conjunction, an EDFA is inserted at the end of the ROADM module in order to comply with the conventional concept [Para05, Keyw05]. The introduced EDFA provides a gain of at least 13dB to 20dB and operates within an input power range of -12 dBm to -20 dBm with a possible noise figure of less than 6 dB. Four channels of C-band: Channels 5, 7, 8, and 9 are transmitted again (at 10 Gbps) in order to emulate a metro network scenario where Channel-5 is dropped, Channel-8 is made expressed, while Channels 7 and 9 are added externally through the ROADM's add-ports. The characteristics of other optical equipments and the simulation environments remain the same as described in previous chapters (Sections 4.2.1 and 3.4.1 respectively).

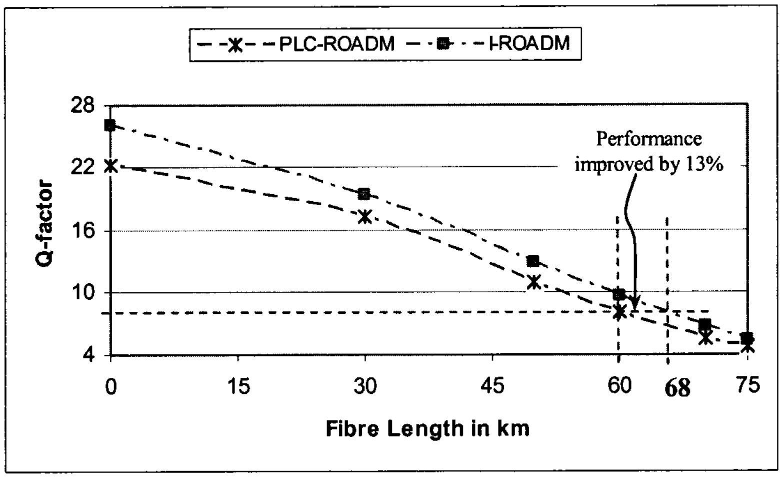


Fig. 5.12. Performance comparison between PLC-ROADM and I-ROADM in terms of Q-factor

The performance of Channel-8 (express-channel) has been measured only in terms of Q-factor (obtained from 4 simulation runs) for two scenarios. In Scenario 1, the power balancing features of I-ROADM is deactivated. Hence, the newly added channels remain 4 dB to 7 dB stronger than the express-channel and the model works as a usual PLC-based ROADM module. In Scenario 2, the power balancing feature of the I-ROADM is activated. The performance for both the scenarios is depicted in Fig. 5.12 in terms of Q-factor as a function of fibre span. The only objective of this simulation is to observe how long the express-channel can travel beyond the ROADM module in such network scenarios.

Fig. 5.12 depicts the Q-factor performance as a factor of the fibre length. In the case of a typical PLC-ROADM module without power balancing, the Q-factor is a decreasing function of the fibre length with a faster decrease as the length becomes longer than 45 km and it is observed that a fibre length of 60 km can be used at a transmission speed of 10 Gbps (for an express-channel at 60 km, Q-factor = 8 BER $\approx 10^{-16}$, Received Optical Power = -22.2 dB). However the performance curve of I-ROADM has similar characteristics and due to its power balancing features the distance is increased to 68 km for the same FEC level, thus improving the overall performance on an average by 13% to 15%. Here the simulation comparisons are performed for a single fibre span. The performance of I-ROADM will certainly be more significant if multiple fibre spans with EDFAs are considered, or if the channel spacing is further reduced.

5.4. Concluding Remarks

In this chapter, a hybrid architecture for ROADM subsystem has been proposed that integrates the best features of the latest PLC- and WSS-based ROADM modules. The proposed Hybrid-ROADM provides the lowest loss for express-channels than any other existing ROADM designs that makes it suitable for high channel count applications without being accompanied by pre- and post-optical amplifiers. The express-channels would now be able to travel longer distance without amplification if the network is equipped with the proposed Hybrid-ROADMs rather than the PLC-[DuPo05], [JPLC06] and the WSS-based subsystems [JWSS06], [WsMe05].

The proposed Hybrid-ROADM introduces a perfect balance between the features of *All-Colorless* ports and *Costs* with its unique feature of having the lowest insertion loss for express channels. Since the high manufacturing cost is still a major constraint for the WSS-based ROADMs and the PLC-based ROADMs are still suffering for their high insertion losses, a combination of both these architectures and their best features will provide a better solution indeed for the next generation optical networks.

The detailed features of developing a transparent ring-to-ring interconnection have also been introduced in this chapter that will definitely help the service providers to integrate the ROADM subsystems into their next generation network in more dynamic ways. The importance of broadcasting signals with equal power levels has also been addressed in this chapter and an attempt has been made on developing an Intelligent ROADM (I-ROADM) subsystem. The controls of I-ROADM can be improved further by developing some new techniques to balance the OSNR/Q-factor level among different channels. These I-ROADMs can be deployed in near future to demonstrate a dynamically provisioned wavelength network which will be described briefly in Chapter 7.

CHAPTER 6: CONCLUSION

The thesis has concentrated on the integration of ROADMs into next generation metro optical network. Detailed design schemes have been presented revealing some important design facts that will help the network developers to integrate the service of ROADMs into their networks in more efficient and cost-effective way.

In order to characterize the performance of ROADM and its behavior in the network, a ROADM prototype was acquired, and simulation models were developed and verified through detail testing in a metro network testbed. The developed simulation models for the reconfigurable optical equipments can easily be configured according to their available specification sheet. With the help of these simulation models, researchers will be able to design and simulate complex network scenarios for their next generation network with an acceptable accuracy.

In order to reduce the loss and the cost within the ROADM module, the thesis has contributed to the development of a hybrid architecture for ROADM subsystems. The proposed Hybrid-ROADM combines the best features of the existing ROADM designs with its unique feature of providing the least loss for express-channels that will eventually reduce the CAPEX and OPEX for the overall network.

The thesis also reveals several other ways of integrating ROADMs into the future metro optical networks. The features of reconfigurable transparent ring-to-ring interconnection and the idea of developing Intelligent ROADM (I-ROADM) subsystems are proposed in this thesis. The transparent interconnections will sweep the costly O-E-Os and OXCs from the network, while the proposed I-ROADMs will play a significant role on improving the control of ROADMs and making them ready for the next generation dynamically provisioned wavelength network. I believe that researchers involved in the planning and the designing of next generation metro optical network will be highly benefited from the models, architectures, and the results presented in this thesis.

CHAPTER 7: FUTURE WORKS

In near future, my plan is to develop a Dynamically Provisioned Optical Network (DPON) where lightpaths will be assigned dynamically according to the traffic demands in the network. With the increase in applications such as video streaming, and broadband services, customers are always asking for more bandwidth. Service providers are considering giving more control to the customers in terms of operation and management of the network. However, it is still uncertain about the level of control that service providers should provide and it is also a big concern in terms of security issue. On the other hand, from the end users' point of view, customers do not want to take hazards to control all the parameters in the network as long as they can ensure a secure bandwidth for their communications. DPON will help the service providers to dynamically reconfigure the lightpaths according to the customer needs without giving any hassle to the customers, or the service providers. Certainly, the control of the proposed I-ROADMs (described in Chapter 5) has to be improved further that will play the most important role in the lightpath provisioning in DPON. An experimental setup is planned to be implemented in order to demonstrate DPON in near future that is briefly discussed in the following section.

7.1. Dynamically Provisioned Optical Network

Fig. 7.1 demonstrates the setup that I am planning to develop for a Dynamically Provisioned Optical Network. Initially four I-ROADM nodes can be setup at the designated positions in two metro ring networks and can establish a bi-directional communications. For simplicity of illustration, I show only unidirectional diagram in Fig. 7.1. The proposed experimental setup will mainly cover two distinguished aspects:

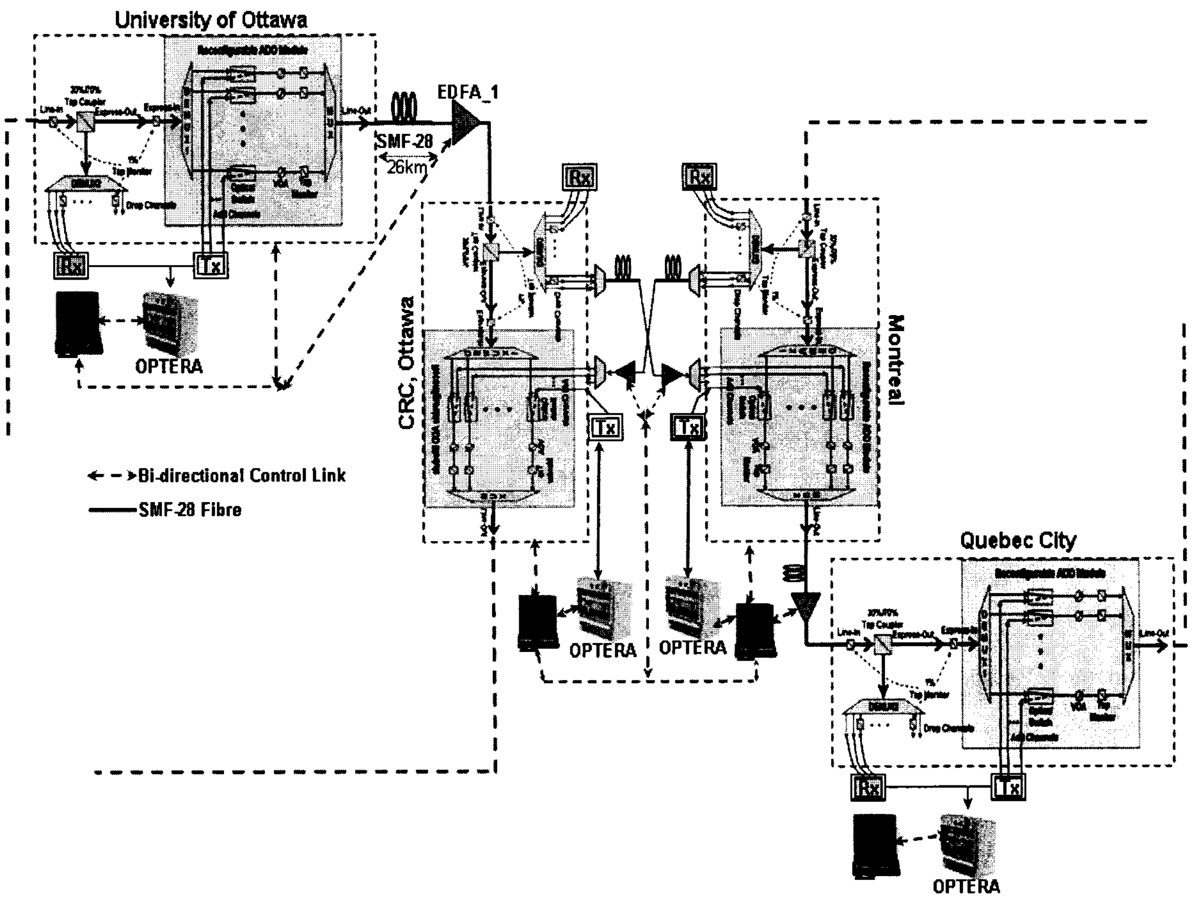


Fig. 7.1. The future plan to setup four I-ROADM nodes in order to develop a Dynamically Provisioned Optical Network (DPON)

1) *Transparent Ring-to-Ring Interconnection:* This is one of the most important features provided by the 3rd generation ROADM modules as demonstrated earlier in Section 5.2. As shown in Fig. 7.1, clients in *Ottawa* (both *U of Ottawa* and *CRC*) can be part of a metro ring network while clients in *Montreal* and *Québec City* can be part of another metro ring network. By connecting the respective Add/Drop ports between the *CRC* and the node in *Montreal*, it is possible to establish the interconnection between two rings.
2) *Dynamic Lightpath Provisioning:* In order to test the experiment for dynamic lightpath provisioning, my initial plan is to transmit four wavelengths from the node at *University of Ottawa* – two of them will be intended for the node in *Québec City*, while the other

two are for *CRC* and *Montréal* respectively. A fifth channel will be launched that will basically distribute the control information throughout the whole network.

Whenever a client will want to communicate with another client in the network, he/she will first look for the available *free* channels and will send the *header* information (`source node + destination node + designated channel number`) through the control channel. Every node receiving new control information will broadcast it to its adjacent nodes. According to the control (*header*) information, a separate control interface can be developed that will automatically adjust the add/drop ports of the ROADMs. For example, if a client at *University of Ottawa* wants to send information to a client in *Québec City* using Channel-M then the other nodes (*CRC* and *Montréal*) in between the source-destination nodes can simply drop and add Channel-M respectively to establish the demanded lightpath. Once the connection (i.e. the lightpath) is established, the source client would be able to send data to the destination client. If the established lightpath is left unused for a certain period of time, the designated channel will be declared *free* again that can be reassigned to setup a new lightpath.

Each client can use personal computers connected with Electrical-to-Optical (E>O) and Optical-to-Electrical (O>E) converters to send and receive information from the networks respectively. Nortel's *Optical Metro* (formerly known as *OPTera*) [Nort06] can be used to provide high speed optical signals, while my proposed I-ROADM modules would be able to provide equalized optical power levels among different channels throughout the network. I believe necessary supports from our collaborators will be available in future to demonstrate the performance of this Dynamically Provisioned Optical Network.

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APPENDIX A: DUPONT'S PLC BASED ROADM

In this thesis, experimental measurements are performed using *i*ROAD™ 1600 ROADM module manufactured by DuPont Photonics Technologies [DuPo06]. The iROAD™ 1600 is a 16-channel integrated Planar Lightwave Circuit (PLC)-based Reconfigurable Optical Add/Drop Multiplexer (ROADM) with 100 GHz channel spacing. Any combination of channels on 16-channel grid can be dropped, or added in this module that is manufactured based on Gaussian Arrayed Waveguide Grating (AWG). Fig. A.1 shows an optical block diagram of the module.

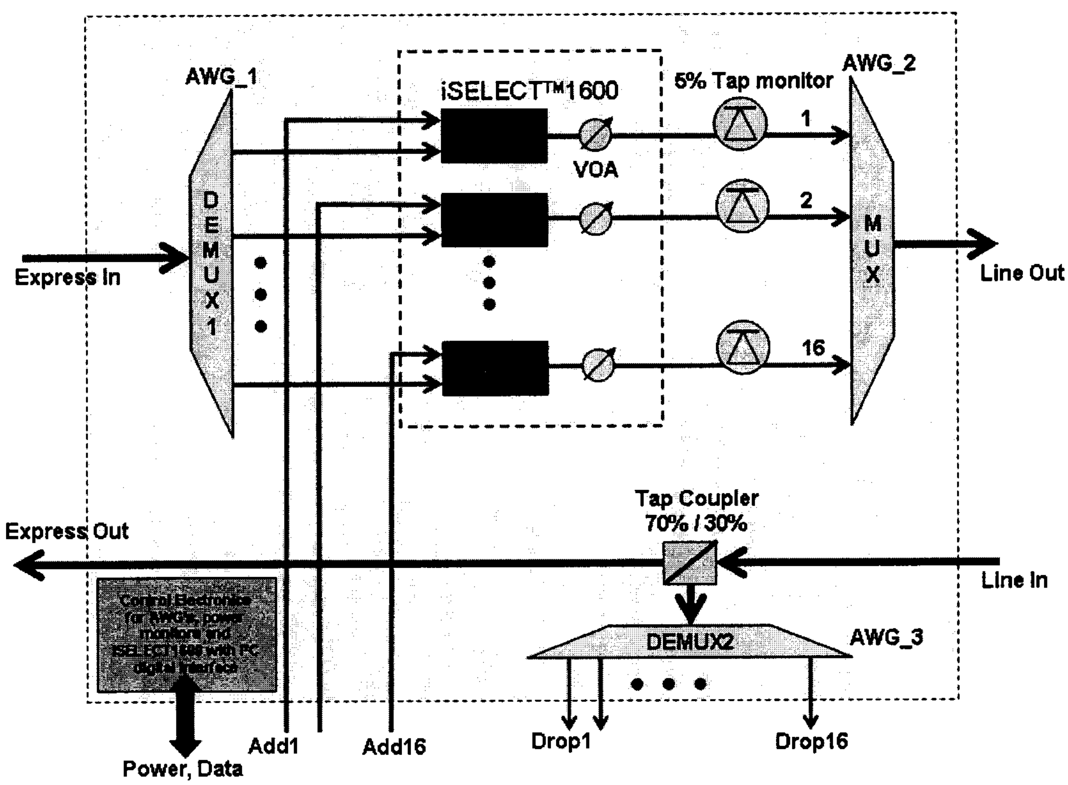

Fig. A.1. Optical block diagram for iROAD™ 1600 ROADM module (Courtesy: DuPont Photonics Technologies)

*i*SELECT™1600 within the module works as 2x1 thermo-optic switches for each channel that can select either the express-, or the add-channel for the output. Only 4 channels (channels 5, 7, 9 and 11) out of 16 contain tap monitors for monitoring the power, while each channel contains a VOA that provides the option for power balancing among the channels. The specification sheet and the wavelength plan for the ROADM module provided by DuPont are shown in Tables A.1 and A.2.

TABLE A.1. OPTICAL SPECIFICATIONS FOR *i*ROAD™ 1600 ROADM

Parameter		Unit	Min	Typical	Max	Comment
Total Channels				16		
Channels Meeting Specifications				4		Please see Table 2.
Channel Spacing		GHz		100		
Passband		GHz	25			*Passband is defined for internal filters*
Ripple Express-In to Line-Out		dB			3.0	*Within the passband*
Polarization Dependent Loss (PDL)	Express-In to Line-Out	dB			0.5	*At minimum attenuation*
Polarization Dependent Loss (PDL)	Line-In to Express-Out	dB			0.2	
Polarization Dependent Loss (PDL)	Add to Line-Out	dB			0.5	
Polarization Dependent Loss (PDL)	Line-In to Drop	dB			0.4	
Insertion Loss (IL)	Express-In to Line-Out	dB			10.0	
Insertion Loss (IL)	Line-In to Express-Out	dB			3.0	
Insertion Loss (IL)	Add to Line-Out	dB			6.0	
Insertion Loss (IL)	Line-In to Drop	dB			9.0	
Chromatic Dispersion		ps/nm	-10		+10	
Adjacent Channel Crosstalk		dB	25			
VOA attenuation range		dB	15	20		*Possible to attenuate until 20dB.*
Switching time		ms			3	
VOA attenuation setting time		ms			10	
VOA setting resolution		dB	0.1			
Extinction Ratio		dB	45			*Ratio of the power defined for logic level 1 and level 0.*
Polarization Mode Dispersion (PMD)		ps			0.7	

(Courtesy: DuPont Photonics Technologies)

TABLE A.2. WAVELENGTH PLAN FOR THE *i*ROAD™ 1600 ROADM MODULE

Channel Number	Frequency (THz)	Wavelength (nm)
1	194.10	1544.526
2	194.00	1545.322
3	193.90	1546.119
4	193.80	1546.917
5	193.70	1457.715
6	193.60	1548.515
7	193.50	1549.315
8	193.40	1550.116
9	193.30	1550.918
10	193.20	1551.721
11	193.10	1552.524
12	193.00	1553.329
13	192.90	1554.134
14	192.80	1554.940
15	192.70	1555.747
16	192.60	1556.555

(Courtesy: DuPont Photonics Technologies)

APPENDIX B: SIMULATION MODELS FOR THE AON TESTBED

The All-Optical Network (AON) system testbed includes several other components installed with the ROADM module. Simulation models are developed using VPI simulation tool [VPIP06] for each of the modules according to its available spec sheet. The following few subsections describe the simulation models developed for Transmitters (Txs)/Receivers (Rxs), Photonic Cross Connects (PXCs), Erbium Doped Fibre Amplifiers (EDFAs), Single Mode Fibres (SMF-28), and Arrayed Waveguide Gratings (AWGs) and their parameter settings. A list of experimental equipments and their specific model numbers are mentioned at the end of this appendix.

B.1. Global Parameter Settings:

In VPI simulation, some parameters are likely to be assigned globally that remains active for all the simulation models developed in that settings. However for the simulations presented in this thesis, only the following parameters are changed in the global parameter settings, and the rest of them are used as default.

TABLE B.1. GLOBAL PARAMETER SETTINGS

Parameters	**Value**	**Unit**
Global		
TimeWindow	1024/10e9	S
InBandNoiseBins	ON	
SampleRateDefault	320e9	Hz
BitRateDefault	2.5e9	bit/s
Transmitter		
Wavelength_Channel5	1547.72	nm
Wavelength_Channel7	1549.32	nm
Wavelength_Channel8	1550.12	nm
Wavelength_Channel9	1550.92	nm
TxExtRatio	30	dB
TxPower	3.8	dBm

B.2. Transmitter (Tx)

Fig. B.1 depicts the internal structure of an externally-modulated transmitter. The Pseudo Random Bit Sequence (PRBS) module generates bit sequences with a probability of 0.5 that are later coded by Non-Return-to-Zero (NRZ) pulses. A Mach-Zender Modulator (MZM) is used to externally-modulate the optical pulse generated by the continuous wave laser (LaserCW). For the entire transmitter module, only the following parameters (shown in Table B.2) are changed according to the specification sheet available at CRC for the AON-testbed.

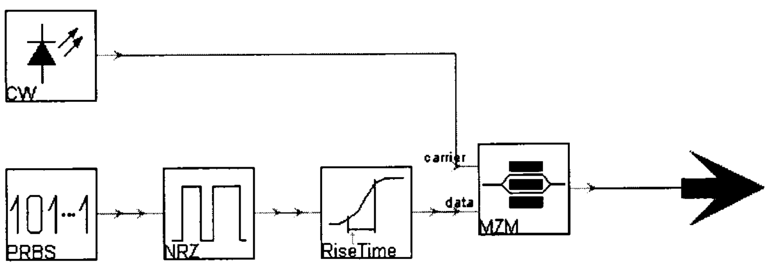

Fig. B.1. Internal diagram for an externally modulated laser

TABLE B.2. PARAMETER SETTINGS FOR TRANSMITTER (TX)

Parameters	Value	Unit
Physical		
Laser_EmissionFrequency	3e8/(Wavelength_Channel7)	S
Laser_AveragePower	10^(TxPower/10)*1e-3	W
ModulatorMZ_ExtinctionRatio	TxExtRatio	dB
Enhanced		
ChannelLabel	Array1Channel1	

B.3. Receiver (Rx)

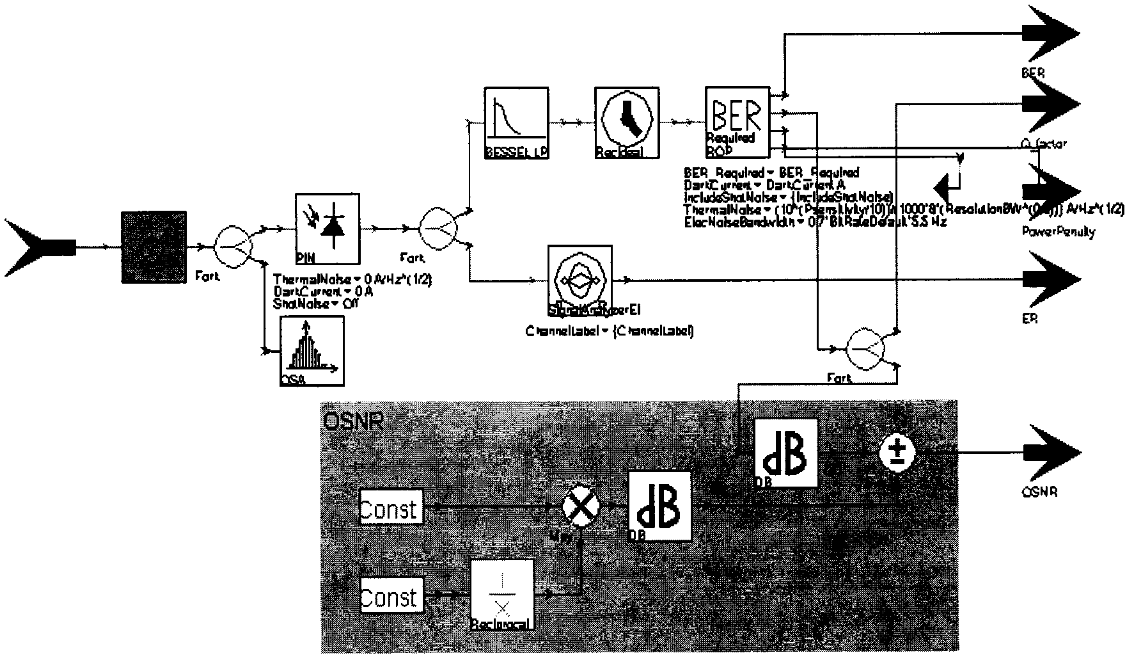

Fig. B.2. Internal diagram for the Receiver (Rx) module

Fig. B.2 reveals the internal structure of my developed receiver module. An ideal Positive-Intrinsic-Negative (PIN) photodiode is used to convert the received optical signal into electrical form. The thermal noises, dark current and shot noise for the diode are set to zero. The PIN photodiode is followed by a *Bessel* low pass filter, a clock synchronizer and Bit Error Rate Tester (BERT) to measure the BER and Q-factor of the corresponding signal. The BERT is basically a *BER_Stochastic* module whose thermal noise is adjusted according to the receiver's sensitivity.

The empirical relation between thermal noise and receiver's sensitivity is given as

$$\text{ThermalNoise} = \frac{\text{Rx\_responsivity}}{\sqrt{\text{NoiseBW}} \text{ x } Q_{\text{eff}}} \text{ x } \frac{10^{\left(\frac{\text{Rx\_sensitivity in dBm}}{10}\right)}}{1000}$$

where the responsivity of the receiver is set to 1, desired effective Q-factor is considered as 8, while noise bandwidth and receiver's sensitivity are considered as 12.5 GHz and -29.7 dBm respectively. Moreover, a signal analyzer and an OSNR meter are setup to measure the Extinction Ratio (ER) and Optical Signal-to-Noise Ratio (OSNR) of the signal. The developed OSNR meter works using the following relation:

$$OSNR_{dB} = Q_{dB} - 10\log\frac{B_o}{B_e}$$

where B_o is defined as the Resolution Bandwidth (RBW) of the photo-detector and B_e is defined as the electrical bandwidth of the receiver filter. Table B. 3 shows the parameter settings for the Rx module.

TABLE B.3. PARAMETER SETTINGS FOR RECEIVER (RX)

Parameters	Value	Unit
Physical		
BER_Required	1e-15	
DarkCurrent	33.95e-6	A
IncludeShotNoise	Yes	
Enhanced		
ChannelLabel	Array1Channel1	
ChannelFrequency	3e8/(Wavelength_Channel7)	Hz
OSNR Meter		
ResolutionBW	12.5e9	Hz
ElectricalBW	35e9	Hz

B.4. Photonic Cross Connect (PXC)

The 8x8 PXC module is developed using 1x8 and 8x1 switches that adds the ability of switching optical signals from any inputs to any of the output ports (Fig. B. 3). The internal construction of a 1x8 switch module is depicted in Fig. B. 4 that basically consists of several 1x2 optical switches – each of which can be controlled by applying a control signal. The detailed settings of the controlled parameters are displayed in Table B. 4.

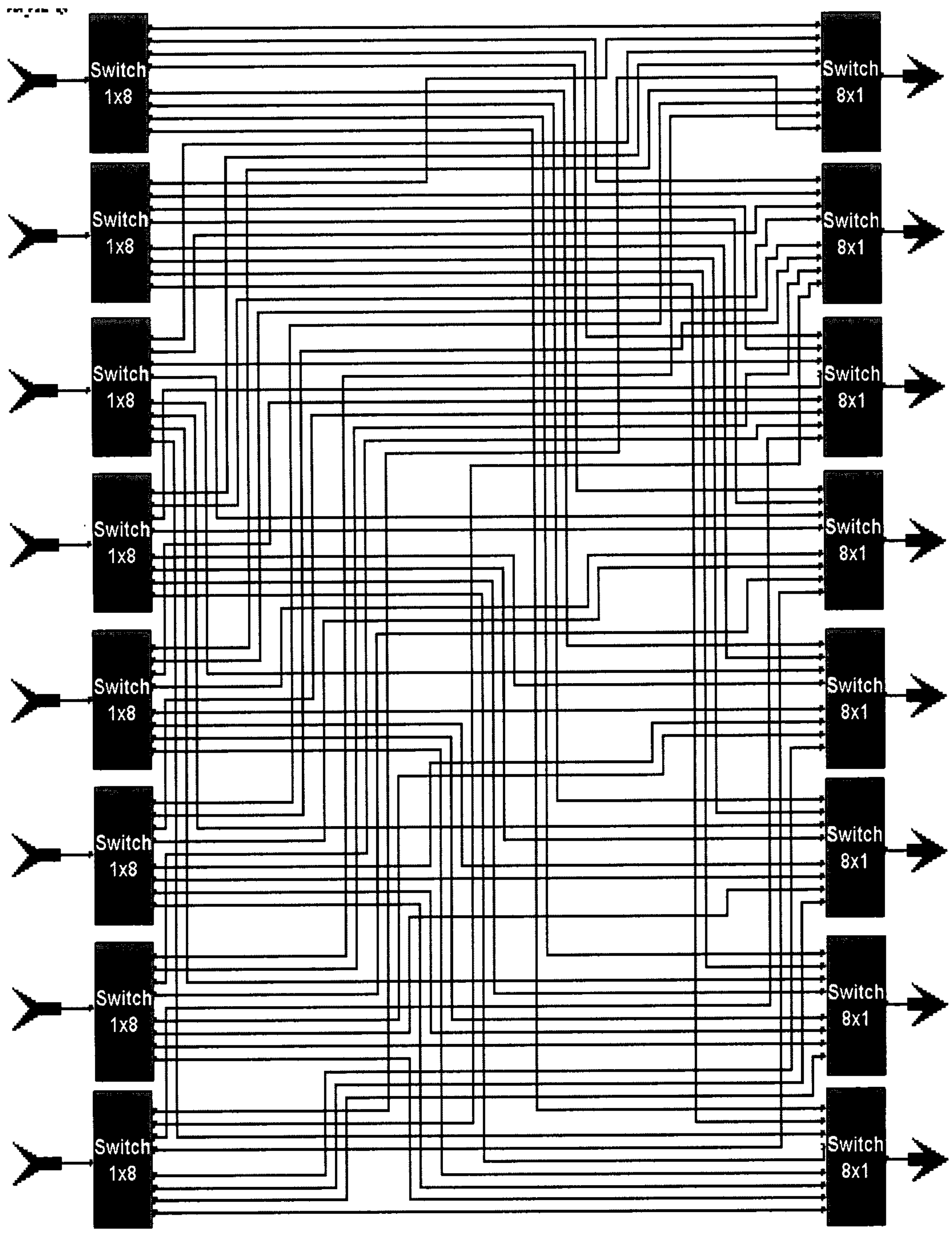

Fig. B. 3. The internal construction of the PXC model

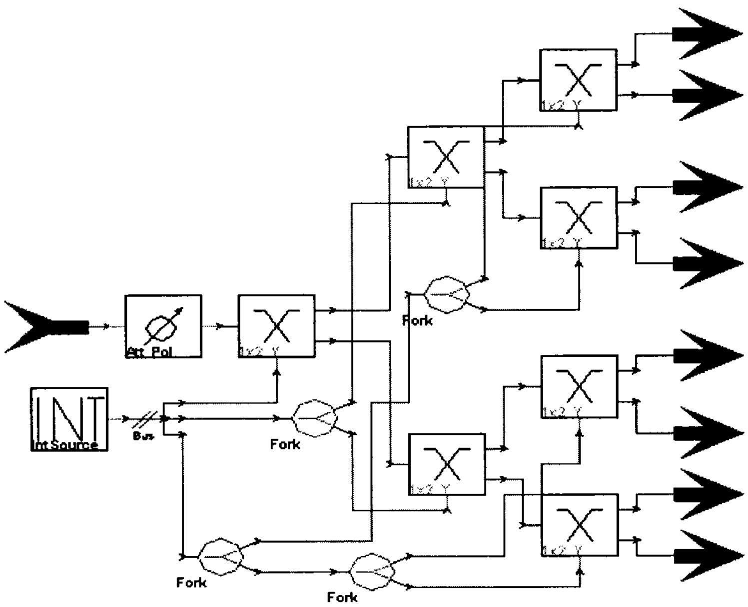

Fig. B. 4. Internal construction of a 1x8 switch.

TABLE B. 4. CONTROL PARAMETER SETTINGS FOR THE PXC MODULE

Parameters	Value	Unit
Physical		
InsertionLoss	0.0	dB
CrossTalk	50	dB
Input_S0	0 0 0	
Input_S1	0 0 1	
Input_S2	1 1 1	
Input_S3	0 1 1	
Input_S4	1 0 0	
Input_S5	1 0 1	
Input_S6	1 1 0	
Input_S7	1 1 1	
Output_S0	0 0 0	
Output_S1	0 0 1	
Output_S2	1 1 1	
Output_S3	0 1 1	
Output_S4	1 0 0	
Output_S5	1 0 1	
Output_S6	1 1 0	
Output_S7	0 1 0	
CrossPathLoss	3.7	dB
ThroughPathLoss	2.5	dB
PDL_PXC	0.4	dB

This PXC module simulates an 8x8 space switch matrix that is controlled by the parameter settings shown in Table B. 4. For example, to connect *Input_S2* to *Output_S7*, a sequence has to be provided so that *Input_S2* goes to *Output_S7* and also *Output_S7* receives signal from *Input_S2*. Hence, for *Input_S2*, the sequence will be ***1 1 1*** while for *Output_S7*, it will be ***0 1 0***.

B.5. Erbium Doped Fibre Amplifier (EDFA)

Two different sets of simulation models are developed for EDFAs in order to associate with the first and second stage of fibres respectively. The internal construction of the first stage EDFA is shown in Fig. B. 5 that satisfies the available spec sheet at CRC. The Polarization Beam Separator (PBS) module first separates the incoming optical signal into *X* and *Y* polarized beams and the amplifier blocks provide the desired gain (≈ 20dB) with the designated polarization sensitivity (≈ 300e^{-3} dB). Finally the Polarization Beam Combiner (PBC) combines the separated beams together at the output. The amplifier blocks provide a noise figure of 6.0 dB.

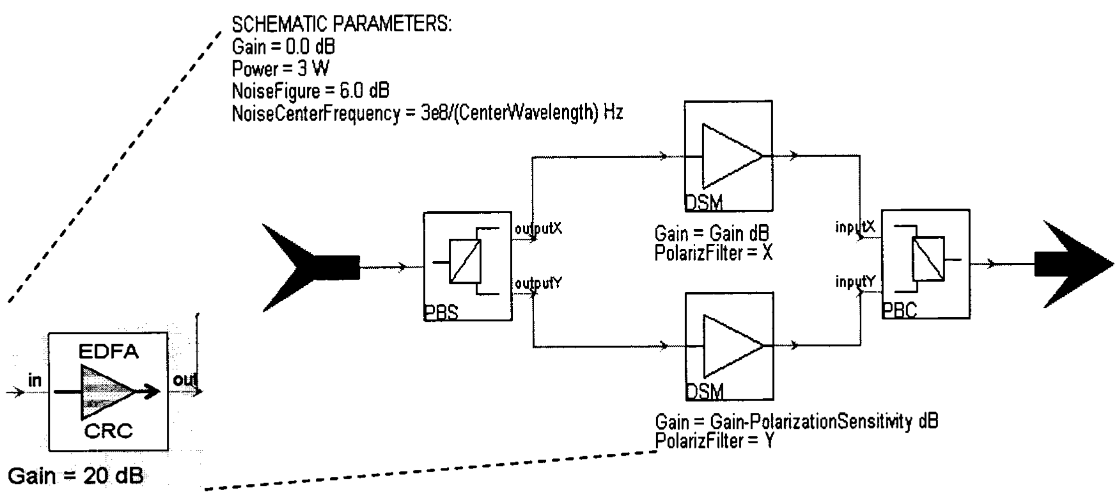

Fig. B. 5. Internal construction of the 1st stage EDFA module

An individual module is developed only for the second stage EDFAs in order to incorporate more Amplifier Spontaneous Emission (ASE) noise into the optical signals (Fig. B. 6). For that purpose, an external noise source is installed within the module that inserts additional White Gaussian noise into the system.

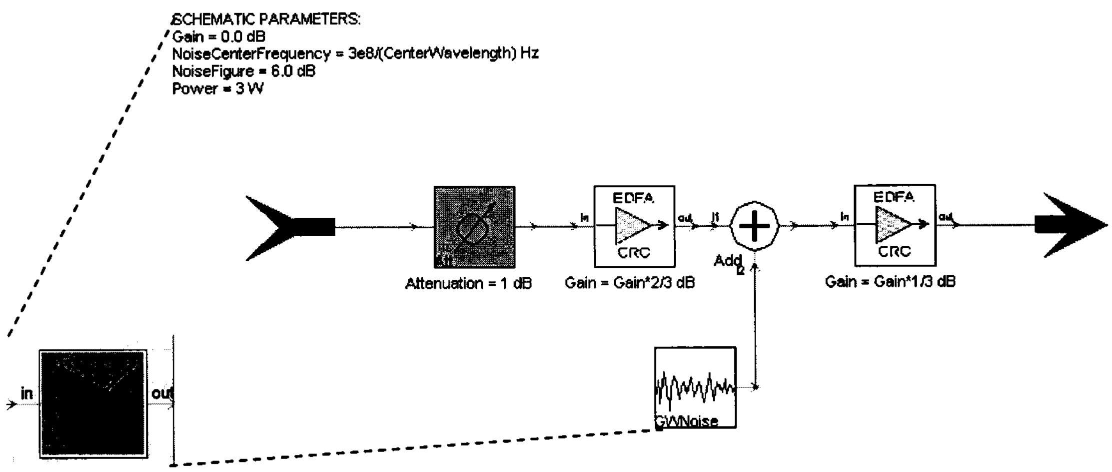

Fig. B. 6. Internal construction of the 2nd stage EDFA module

B.6. Single Mode Fibre (SMF-28)

The schematic diagram for a Single Mode Fibre (SMF-28) is shown below (Fig. B.7). The SMF-28 fibres provide a loss around 0.2 dB/km with a chromatic dispersion of 17 ps/nm/km and PMD of 0.2 ps/km$^{1/2}$.

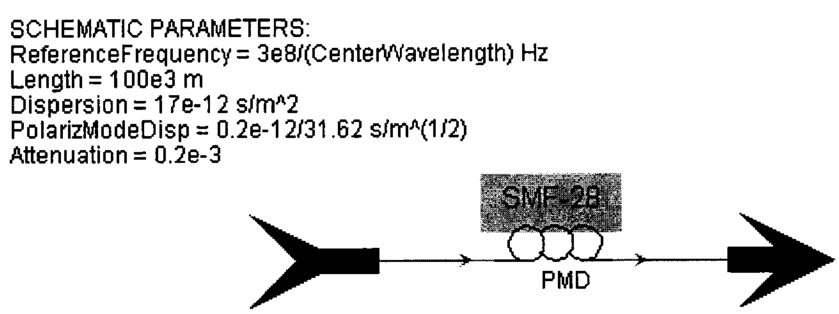

Fig. B. 7. Schematic diagram for SMF-28 fibre

B.7. Arrayed Waveguide Grating (AWG)

Simulation models are developed for 16-channel Muxs/DeMuxs that are basically Arrayed Waveguide Gratings (AWGs). Fig. B. 8 depicts the internal construction of an AWG-MUX module that contains a Gaussian filter, attenuators and crosstalk generator modules for each of its 16 channels. The adjacent-channel crosstalk for the designated AWG is less than 23 dB while the non-adjacent channel crosstalk is defined as 30 dB. Each of the AWGs provides an insertion loss less than 3.5 dB.

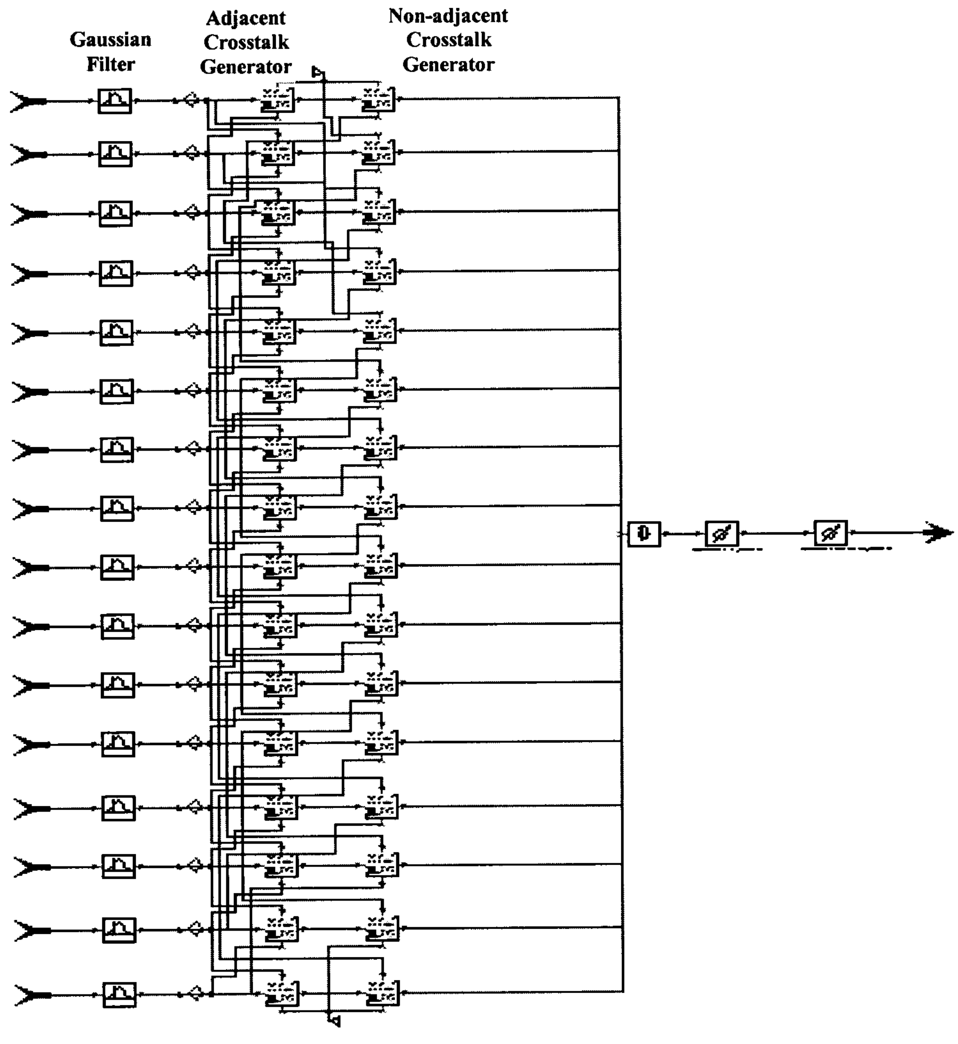

Fig. B. 8. Internal Construction of an Arrayed Waveguide Grating (AWG)-Mux

B.8. List of Experimental Equipments

TABLE B. 5. LIST OF EQUIPMENTS USED IN EXPERIMENT

Function	Manufacturer	Model
Tx / Rx	Nortel Inc.	Optera 80 / OCLD OC-48 STM-16
PXC (8x8)	OMM	OMM 8x8
AWG	BaySpec Inc.	16-channel AWG
ROADM	DuPont Photonics	*i*ROADM^{TM}1600
VOA	JDS Uniphase	HA1 Optical Attenuator
EDFA	BaySpec Inc.	C-band Series; # 86142 B
Tap Coupler	JDS Uniphase	50%; 1%
OCPM	BaySpec Inc.	32-channel, 100 GHz spacing
OSA	Hewlett Packard	70951B; Range 600-1700 nm
BERT	Hewlett Packard	70820A Microwave Transition Analyzer
Eye Analyzer	Hewlett Packard	54120B Digitizing Oscilloscope Mainframe
Fibre	Corning Inc.	SMF-28

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