ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

PHYSICAL LAYER IMPAIRMENTS AWARE DYNAMIC LIGHTPATH PROVISIONING IN MIXED LINE RATE WDM NETWORKS

Ph.D. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

FİZİKSEL KATMAN BOZUCU ETKİLERİ GÖZETİLEREK ÇOKLU VERİ İLETİM HIZLI DALGABOYU BÖLÜMLEMELİ ÇOĞULLAMA AĞLARINDA DİNAMİK IŞIKYOLU KURULUMU

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OCAK 2014

Haydar ÇUKURTEPE, a Ph.D. student of ITU Graduate School of Science Engineering and Technology 504052507 successfully defended the thesis entitled **"PHYSICAL LAYER IMPAIRMENTS AWARE DYNAMIC LIGHTPATH PROVISIONING IN MIXED LINE RATE WDM NETWORKS"**, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my spouse and daughter,

FOREWORD

There had been many late nights and early mornings, and after all the work, it is a great pleasure to conclude that the thesis is over. I am really honored to be writing these lines.

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January 2014 Haydar ÇUKURTEPE

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ABBREVIATIONS

ASE	: Amplified Spontanous Emission
BB	: Best Bit-Error Rate
BBR	: Bandwidth Blocking Ratio
BER	: Bit-Error Rate
CAPEX	: Capital Expenditure
CD	: Chromatic Dispersion
DCF	: Dispersion Compensation Fiber
DeMUX	: Demultiplexer
DPSK	: Differential Phase Shift Keying
DQPSK	: Differential Quadrature Phase Shift Keying
DP-QPSK	: Dual Polarization Quadrature Phase Shift Keying
EDFA	: Erbium Doped Fiber Amplifier
EON	: European Optical Network
FBG	: Fiber Bragg Grating
FF-W-GB	: First-Fit Worst-Case (with) Guard Band
FWM	: Four Wave Mixing
FWIA	: Fixed Wavelength Interval Allocation
GB	: Guard Band
IA	: Impairment Aware
I-ALPD	: Impairment-Aware Launch Power Determination
IM	: Inverse Multiplexing
LCP	: Least Congested Path
MH	: Minimum Hop
MLR	: Mixed Line Rate
MSD	: Maximum Spectral Distance
MUX	: Multiplexer
NMS	: Network Management System
OEO	: Optical-Electronic-Optical (Conversion)
OOK	: On-Off Keying
OSNR	: Optical Signal-to-Noise Ratio
OXC	: Optical Cross Connect
PCE	: Path Computation Element
PLI	: Physical-Layer Impairment
PMD	: Polarization Mode Dispersion
QoT	: Quality of Transmission
ROADM	: Reconfigurable Optical Add Drop Multiplexer
RWA	: Routing and Wavelength Assignment
SP	: Shortest Path
SPM	: Self-Phase Modulation
SSMF	: Standard Single Mode Fiber

WBA : Worst-case Best-case Average
WDM : Wavelength Division Multiplexing
W-RWA : Weighted Routing and Wavelength Assignment
WSS : Wavelength Selective Switch
XPM : Cross-Phase Modulation
XT : Crosstalk
10G : 10 Gbps
40G : 40 Gbps
100G : 100 Gbps

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PHYSICAL LAYER IMPAIRMENTS AWARE DYNAMIC LIGHTPATH PROVISIONING IN MIXED LINE RATE WDM NETWORKS

SUMMARY

The increase in diversity of traffic demands on the Internet requires migration from legacy (10G) optical backbone networks to higher (40G/100G) line rates. Since it is impractical and perhaps even undesirable to upgrade all 10G transmission components to higher line rates at once, WDM optical networks support mixed line rates (MLR) to meet the requirements for both diversity and capacity increase, together. MLR refers to an architecture where different line rates on different wavelengths can coexist on the same fiber.

MLR architectures can be built over transparent, as well as translucent or opaque optical networks. In opaque networks, transmission occurs over point-to-point links, where the signal is regenerated at every node. In translucent networks, the signal remains in optical domain as much as it can. In transparent networks, the transmission occurs in optical domain. The optical channels cannot be processed at intermediate nodes on optical level but can be switched. Along the transparent optical path, a signal undergoes a number of physical-layer impairments (PLI), and its quality degrades as it travels through several optical components. A major impairment is the accumulated noise, mainly due to amplified spontaneous emission (ASE) and crosstalk (XT). Dispersion, attenuation and power loss due to optical components are some of other linear impairments on a signal. Optical transmission channels are also affected by non-linear impairments such as self-phase modulation (SPM) and cross-phase modulation (XPM), which are the shifts in the phase of a signal caused by the change in intensity of the signals itself or on the neighboring wavelengths, respectively.

In dynamic traffic scenario, a connection request comes to the network, stays for a while, and terminates. A lightpath is set up for each connection request as it arrives, and it is released after the requested amount of time. Finding an appropriate route and assigning a wavelength to a given connection request is called the Routing and Wavelength Assignment (RWA) problem. The objective of the problem is to set up lightpaths and assign wavelengths in a manner that minimizes the amount of connection blocking, or that maximizes the number of connections that are established in the network at any time. Lightpath provisioning, in addition to RWA, deals with connection management and quality of signal. Impairment-aware (IA) lightpath provisioning problem is a cross-layer optimization problem, which finds the appropriate path and wavelength at the network layer and assures the acceptable signal quality at the physical layer.

For 10G line rate signals, on-off keying (OOK) with direct detection is the most commonly used transmission technique. Higher bandwidth results in a linear increase in noise level of the intensity modulated channel. Thus, higher line rates (e.g., 40G, 100G) require advanced modulation techniques such as: differential quadrature

phase shift keying (DQPSK) and dual-polarization quadrature phase shift keying (DP-QPSK). DQPSK and DP-QPSK modulated signals are highly susceptible to PLIs. Moreover, coexistence of OOK signals with advanced modulation formats induces high XPM on xPSK signals. So, accounting for PLIs during the provisioning phase, which is an important problem in single-line-rate WDM networks acquires even larger importance in MLR networks. Hence, for MLR networks, the well-known impairment-aware lightpath provisioning problem must account for these two new dimensions: the XPM effect of OOK channels on advanced modulation formats, and the trade-off between capacity and optical reach.

Although various valuable studies exist on the network design problem for MLR networks considering the static traffic case, there are only a few studies on impairment-aware dynamic lightpath provisioning in MLR networks. In this thesis, we studied the impairment-aware lightpath provisioning problem for dynamic connection requests in MLR networks. Given, a dynamic connection request with a given rate, physical topology, number of wavelengths carried by each fiber, current network state, and PLI parameters, our aim is to determine the route and wavelength over which the lightpath should be set up, in order to be able to maximize the number of established connections while satisfying the given bit-error rate (BER) for the incoming connection, and to avoid disrupting the existing lightpaths. We also evaluate the launch power of the lightpath to maximize the established connections.

In this thesis, we propose various heuristic algorithms to solve the problem. We first investigate the effects of inverse multiplexing (IM), which is a technique that tries to exploit the advantage of transmitting the signals with low line rates, where the high line rate is not possible due to impairments. The network layer applications enable to inversely multiplex the connection requests with high line rates into smaller line rates at the source node, propagate them separately over a transparent MLR network, and then combine them back at the destination node. We propose various IM-based schemes to account for impairment-aware dynamic lightpath provisioning in MLR optical networks. The proposed schemes use three different path-selection algorithms: shortest path (SP), minimum hop (MH) path, and least congested path (LCP). We employed two different wavelength-assignment schemes with each path-selection algorithms: Best BER (BB) and maximum spectral distance (MSD).

We also propose two novel approaches for the IA dynamic lightpath provisioning problem. The first approach, Fixed Wavelength-Interval Allocation (FWIA), partitions the wavelengths into groups, assigns each group to a different line rate, and establishes lightpaths with different modulation formats over the assigned wavelength groups. This approach exploits the advantage of placing different modulation formats into separate channels and they have adjacency with other modulation formats only at the boundaries of intervals. The second algorithm is the Weighted-RWA (W-RWA), which captures the instantaneous state of the network and assigns weight values according to affecting impairments using an auxiliary graph. The algorithm works for minimizing the effects of XPM and leaves more feasible wavelengths for future requests, while avoiding damaging already established lightpaths. Since the weight assignment process can be made off-line, the W-RWA makes use of idle time before any request comes. We evaluated our algorithms through simulations, and compared with existing methods.

Another important parameter for signal quality is the launch power of both the actual signal and the neighboring signals. In the last part of the thesis, we evaluated the effects of launch power, and proposed two practical approaches for appropriate launch power determination to maximize the established connections. In Worst-case Best-case Average (WBA), average optical reach for worst and best cases is used to determine the launch power. In Impairment-Aware Launch Power Determination (I-ALPD), impairments along the path are considered in a practical way to determine the launch power. I-ALPD tracks the current state of the network, and assigns weight values to the wavelengths according to the impairments. I-ALPD uses an auxiliary graph to capture the PLIs on channels with a weight assignment scheme. The proposed algorithms are compared with existing approaches. The results indicate that overall network performance can be improved by selecting the appropriate launch powers to establish the lightpaths, considering the current state of the network.

FİZİKSEL KATMAN BOZUCU ETKİLERİ GÖZETİLEREK ÇOKLU VERİ İLETİM HIZLI DALGABOYU BÖLÜMLEMELİ ÇOĞULLAMA AĞLARINDA DİNAMİK IŞIKYOLU KURULUMU

ÖZET

Artarak yayılan İnternet kullanımı ve yeni uygulamalar, İnternette bağlantı ihtiyaçlarını ve ihtiyaçlardaki çeşitliliği artırmaktadır. Bu artış omurga ağlarda kullanılan iletişim hızlarında iyileştirmeler gerektirmektedir, örneğin 10G yerine 40G/100G kullanılması. Ancak ağ bileşenlerinin tümünün aynı anda iyileştirilmesi mümkün olmadığı gibi her zaman istenilen bir şey de değildir. Artan bantgenişliği ihtiyacını Dalgaboyu Bölümlemeli Çoğullama (Wavelength Division Multiplexing, WDM) ile karşılayan servis sağlayıcılar, artan çeşitliliğe çözüm olarak, herbir dalgaboyunda farklı veri iletişim hızında iletişim yapılmasını mümkün kılan Çoklu Veri İletim Hızlı (Mixed Line Rate, MLR) ağları kullanmaya başlamışlardır. MLR, farklı veri iletim hızlı kanalların aynı ağ üzerinde yer alabilmesini sağlayan mimariye verilen isimdir.

MLR mimarisi saydam, yarı-saydam ve opak ağlarda kurulabilir. Opak ağlarda, iletişim noktadan-noktaya hatlar üzerinden gerçekleştirilir. Herbir düğümde sinyal yeniden üretilir. Yarı-saydam ağlarda sinyal mümkün olduğu kadar optik katmanda kalır. Saydam ağlarda ise sinyal ara düğümlerde işlenmez, yalnızca anahtarlanır. Saydam ağlarda, optik sinyal fiziksel katmandaki bozucu etkilere maruz kalır. Bu bozucu etkiler sinyalin ilerlediği yol boyunca birikerek sinyal kalitesinin azalmasına sebep olur. Bu kalite kaybı, hedef düğümde sinyalin doğru olarak okunamamasına sebep olabilir. Gürültü bu bozuklukların en önemlilerindendir ve esas olarak yükselteç gürültüsü ve hat karışımından kaynaklanır. Fiziksel katmandaki diğer bozukluklara örnek olarak; sönümleme, dispersion ve diğer kayıplar sayılabilir. Bunların dışında sinyal, doğrusal olmayan bozukluklardan da etkilenir. Bunlara örnek olarak da, kendi faz modülasyonu (self-phase modulation, SPM), çapraz faz modülasyonu (cross-phase modulation, XPM) karışımı vb. sayılabilir. Bu bozukluklar sırasıyla kendi veya komşu sinyalin yoğunluğunda oluşan değişimlerin sinyal fazında yarattığı bozulmaları ifade eder.

Dinamik ortamlarda, bağlantı istekleri gelirler, belirli bir süre sistemde kalırlar ve sona erdirilirler. Her bir bağlantı isteği için bir ışıkyolu kurulur ve bu ışıkyolu talep edilen bağlantı süresi bitiminde sonlandırılır. Gelen bağlantı istekleri için, ağın o anki durumunu dikkate alarak uygun yol ve dalgaboyunun atanmasına yönlendirme ve dalgaboyu atama (Routing and Wavelength Assignment, RWA) problemi denir. Amaç uygun yol ve dalgaboyunu seçerek, kurulabilecek ışıkyolu sayısının mümkün olduğu kadar artırmak, diğer bir ifade ile bağlantı isteklerinin reddedilme oranının azaltmaktır. Işıkyolu kurma problemi, yönlendirme ve dalgaboyu atama problemine ilave olarak, bağlantı yönetimi ve sinyal kalitesi ile de ilgilenir. Fiziksel katmandaki bozucu etkilerin gözetilerek ışıkyolu kurulumu problemi, ağ katmanında uygun yol

ve dalgaboyu bulunması ile fiziksel katmanda sinyal kalitesinin kabul edilebilir seviyede olmasını sağlaması sebebiyle birden fazla katmanı ilgilendiren bir iyileştirme problemidir.

Omurga ağlarda, 10G veri iletim hızı için aç-kapa modülasyonu (on-off keying, OOK) yaygın olarak kullanılmaktadır. Bu modülasyon tekniği ile yüksek kapasiteli veri iletimi yapılmak istendiğinde sinyal üzerindeki gürültünün etkisi daha da artmaktadır. Bu sebeple yüksek kapasiteli veri iletişimi için gelişmiş modülasyon teknikleri uygulanır, örneğin; "differential quadrature phase shift keying (DQPSK)" ve "dual-polarization quadrature phase shift keying (DP-QPSK)". Bu modülasyon teknikleri fiziksel katmandaki bozucu etkilere karşı oldukça hassastırlar. Ayrıca OOK kanalların, bu modülasyonlar üzerinde yarattığı XPM etkisi önemli bir bozucu etkidir. Bu sebeple, zaten tek iletim hızlı ağlarda önemli olan fiziksel katmandaki bozucu etkilerin gözetilerek ışıkyolu kurulması problemi, çoklu veri iletim hızlı ağlarda daha da önem kazanmaktadır. Problemin iki ilave boyuta daha çözüm getirmesi gerekmektedir; aç-kapa modülasyonlu sinyallerin gelişmiş modülasyonlu sinyaller üzerindeki XPM etkisi ve kapasite-erim dengesi.

Çoklu veri iletim hızlı ağlarda, statik trafik durumu için tasarım problemi konusunda pek çok çalışma olmasına rağmen, dinamik durumlara yönelik yapılmış çalışma sayısı çok fazla değildir. Bu tez çalışmasında, fiziksel katman bozukluklarını dikkate alarak, çoklu veri iletişim hızlı ağlarda dinamik olarak gelen bağlantı istekleri için ışıkyolu kurma problemi ele alınmıştır. Problemde verilenler; dinamik olarak gelen farklı kapasitelerde bağlantı istekleri, fiziksel topoloji, fiziksel hatların taşıyabildiği dalgaboyu miktarı, ağın anlık durumu ve fiziksel katman bozukluklarını dikkate alırken kullanılacak olan parametrelerdir. Problemde istenilen ise; gelen bağlantı isteklerinin mümkün olduğu kadar fazlasını kurabilmek maksadı ile uygun yol ve dalgaboyunun bulunmasıdır. Bunu gerçekleştirirken, hem kurulacak olan ışıkyolunun sinyal kalitesinin kabul edilebilir bit hata oranını karşılaması, hem de sistemde daha önceden kurulmuş olan ışıkyollarının sinyal kalitesinin kabul edilebilir sınırların altına inmesini engellemek gerekmektedir. Bu tez çalışmasında, kurulabilen ışıkyolu miktarını artırmak maksadı ile ışıkyolunun sisteme giriş gücü de ayrıca ele alınmıştır.

Problemin çözümüne yönelik çeşitli sezgisel algoritmalar önerilmiştir. Öncelikle tersine-çoğullama (inverse multiplexing, IM) temelli yaklaşımlar değerlendirilmiştir. Bu yaklaşımda, yüksek veri iletim kapasiteli bağlantı isteğinin, fiziksel katman bozuklukları sebebi ile kurulamaması durumunda, bu istek, daha düşük kapasiteli, birden çok veri iletişim kanalı yardımı ile kurulur. Ağ katmanındaki uygulamalar, tersine-çoğullama tekniği kullanarak, gelen bağlantı isteğinin kaynak düğümde daha düşük bağlantı isteklerine bölünmesini, bu isteklerin herbirinin ayrı iletişim kanalı üzerinden iletilmesini ve hedef düğümde birleştirilmesini mümkün kılmaktadır. Önerilen tersine-çoğullama yaklaşımlı yöntemler üç farklı yol bulma yöntemi kullanır: En kısa yol (Shortest Path, SP), en az sekme (Minimum Hop, MH) ve yoğunluğun en az olduğu yol (Least Congested Path, LCP-BB). Herbir yol bulma yöntemi ile iki farklı dalgaboyu atama yaklaşımı uygulanmıştır: En iyi bit hata oranı (Best BER, BB) ve en uzak aralıklı dalgaboyu (Maximum Spectral Distance, MSD).

Fiziksel katman bozukluklarını dikkate alarak dinamik ışıkyolu kurulumu problemi için önerilen diğer sezgisel yöntemler ise; farklı veri iletişim hızlarına sabit dalgaboyu aralığı atama (Fixed Wavelength-Interval Allocation, FWIA) ve ağırlıklı yönlendirme ve dalgaboyu atama (Weighted-RWA, W-RWA) yaklaşımlarıdır. Bu yaklaşımların ilkinde, herbir veri iletişim hızı için belli bir dalgaboyu aralığı önceden belirlenir, tahsis edilir. Burada amaç farklı modülasyonların birbirleri üzerindeki, özellikle de OOK kanalların diğer modülasyonlar üzerinde etkilerini en aza indirmektir. Ağırlıklı yönlendirme ve dalgaboyu atama yaklaşımda, ağın anlık durumu takip edilir ve bir yardımcı graf kullanılarak fiziksel katmandaki bozukluklara karşılık ağırlık ataması yapılır. Bu yöntem, XPM etkisinin azaltılmasını, var olan ışıkyollarının en azının etkilendiği yolun bulunmasını ve daha sonra gelecek olan bağlantı istekleri için daha fazla uygun yol bırakılmasını hedeflemektedir. Ağırlık ataması, ışıkyollarının kurulması veya serbest bırakılması durumunda yapılacağından, sistemin boşta olduğu zamanı kullanarak yapılması mümkündür. Önerilen algoritmalar var olan algoritmalar ile karşılaştırılmıştır.

Sinyalin kalitesini etkileyen önemli bir faktör de hem sinyalin kendisinin, hem de komşu sinyallerin sisteme giriş gücüdür. Tez çalışmasının son bölümünde sinyalin sisteme giriş gücünün etkisi değerlendirilmiştir. Sinyal giriş gücünün doğru seçilmesi ile bozucu etkileri azaltmak ve kurulabilecek ışıkyolu sayısının artırmak mümkündür. Sinyal giriş gücünün doğru seçilmesi maksadı ile iki yeni yöntem önerilmiştir. Önerilen yöntemler; iyi-durum kötü-durum ortalaması (Worst-case Best-case Average, WBA) ve fiziksel katman bozukluklarını dikkate alan giriş gücü belirleme (Impairment Aware Launch Power Determination, I-ALPD) yöntemleridir. Bu yöntemlerden ilkinde, kötü durum ve iyi durum senaryoları için ışıkyolunun kurulabileceği en uzun mesafeler bulunur. Bulunan mesafelerin ortalaması ve kurulacak ışıkyolunun uzunluğu bilgisi kullanılarak atanacak giriş gücü tespit edilir. Önerilen bir diğer yöntem olan, fiziksel katman bozukluklarını dikkate alan giriş gücü belirleme yönteminde, yol boyunca etkili olan bozukluklar pratik bir şekilde hesaba katılırlar. Bu yöntemde ağın anlık durumu takip edilir ve bir yardımcı graf kullanılarak fiziksel katmandaki bozukluklara karşılık ağırlık ataması yapılır. Önerilen algoritmalar var olan yöntemler ile karşılaştırılmıştır. Sonuçlar, ağın anlık durumu dikkate alınarak uygun sinyal giriş gücü seçilmesinin, gelen istekleri reddetme oranı açısından performans artışı sağladığını göstermiştir.

1. INTRODUCTION

Network operators are facing a continuous increase in terms of diversity of both traffic demands and bandwidth due to new services and bandwidth-consuming applications on the Internet. Since it is impractical and perhaps even undesirable to upgrade all legacy (10G) transmission components to higher line rates (e.g., 40G, 100G) at once, WDM optical networks support mixed line rates (MLR) to meet the requirements for both diversity and capacity increase, together. MLR refers to an architecture where different line rates on different wavelengths can coexist on the same fiber.

MLR architectures can be built over transparent, as well as translucent or opaque optical networks. In opaque networks, data transmission occurs over point-to-point links so that the signal is regenerated at every intermediate node along transmission channel. The regeneration of optical signal is done using optical-electronic-optical (OEO) conversion. In translucent architecture, regenerators are placed sparsely. It eliminates much of the electronic process and allows a signal to remain in the optical domain as much as it can [1].

In transparent networks, OEO conversions are not used at the intermediate nodes. The transmission occurs in optical domain. The optical channels cannot be processed at intermediate nodes on optical level but can be switched. Along the transparent optical path, a signal undergoes a number of physical-layer impairments (PLI) and its quality degrades as it travels through several optical components [1]. A major impairment is the accumulated noise, mainly due to amplified spontaneous emission (ASE) and crosstalk (XT). Optical transmission channels are also affected by non-linear impairments such as self-phase modulation (SPM) and cross-phase modulation (XPM), which are the shifts in the phase of a signal caused by the change in intensity of the signals itself or on the neighboring wavelengths, respectively.

In optical WDM networks, end users communicate with one another via all-optical WDM channels, which are referred to as lightpaths [2]. In dynamic traffic case, a lightpath is set up for each connection request as it arrives, and it is released after some finite amount of time. Finding an appropriate route and assigning a wavelength to given connection requests is called the Routing and Wavelength Assignment (RWA) problem. The objective of the problem is to set up lightpaths in a manner that minimizes the amount of connection blocking, or that maximizes the number of connections that are established in the network at any time. Lightpath provisioning, in addition to RWA, deals with connection management and quality of signal. Impairment-aware (IA) lightpath provisioning problem is a cross-layer optimization problem, which finds the appropriate path and wavelength at the network layer and assures the acceptable signal quality at the physical layer.

For 10G line rate signals, on-off keying (OOK) with direct detection is the most commonly used transmission technique [3]. Higher bandwidth results in a linear increase in noise level of the intensity-modulated channel. Thus, higher line rates (e.g., 40G, 100G) require advanced modulation techniques such as: differential quadrature phase shift keying (DQPSK) and dual-polarization quadrature phase shift keying (DP-QPSK). DQPSK and DP-QPSK modulated signals are highly susceptible to PLIs. Moreover, coexistence of OOK signals with advanced modulation formats induces high XPM on xPSK signals [4, 5]. Accounting for PLIs during the provisioning phase, which is an important problem in single-line-rate WDM networks acquires even larger importance in MLR networks. In MLR networks, the problem has two additional dimensions: the disruptive interaction of different modulation formats, and the trade-off between capacity and optical reach[1].

In this thesis, the impairment-aware lightpath provisioning problem is studied for dynamic connection requests in MLR networks. We first investigate the effects of inverse multiplexing (IM), which is a technique that tries to exploit the advantage of transmitting the signals with low line rates, where the high line rate is not possible due to impairments. The network layer applications enable to inversely multiplex the connection requests with high line rates into smaller line rates at the source node, propagate them separately over a transparent MLR network, and then combine them back at the destination node. We propose various IM-based schemes to account for impairment-aware dynamic lightpath provisioning in MLR optical networks.

[1]Reach is the distance an optical signal can travel before the signal quality degrades to a level that necessitates regeneration [6].

The proposed schemes use three different path-selection algorithms: shortest path (SP), minimum hop (MH) path, and least congested path (LCP). Two different wavelength-assignment schemes are employed with each path-selection algorithms: Best Bit Error Rate (BB) and maximum spectral distance (MSD).

We also propose two novel approaches for IA lightpath provisioning problem. The first approach, Fixed Wavelength-Interval Allocation (FWIA), partitions the wavelengths into groups, assigns each group to a different line rate, and establishes lightpaths with different modulation formats over the assigned wavelength groups. The second algorithm is the Weighted-RWA (W-RWA) scheme, which captures the instantaneous state of the network and assigns weight values according to affecting impairments. The algorithm works for selecting the wavelengths which are less exposed to impairments while trying to leave feasible wavelengths for future requests, and avoiding damaging the existing lightpaths. Since the weight assignment process can be made off-line, the W-RWA makes use of idle time before any request comes.

Another important parameter for signal quality is the launch power of both the actual signal and the neighboring signals. We also evaluate the effects of launch power and propose two practical approaches for appropriate launch power determination. In the Worst-case Best-case Average (WBA), average optical reach for worst and best cases, in terms of impairments, is used to determine the launch power. In Impairment-Aware Launch Power Determination (I-ALPD), impairments along the path are considered in a practical way to determine the launch power. I-ALPD tracks the current state of the network, and assigns weight values to the wavelengths according to the impairments. I-ALPD uses an auxiliary graph to capture the PLIs on channels with a weight assignment scheme.

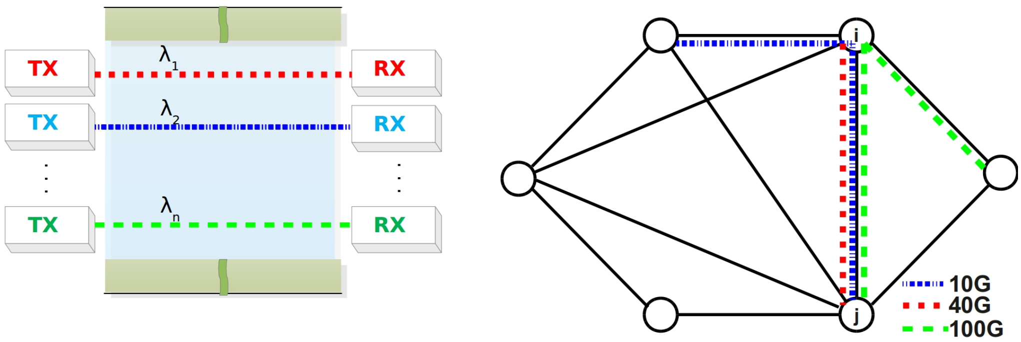
The outline of this thesis is as follows: A brief explanation on the enabling technologies of MLR optical WDM networks and optical transmission are given in Chapter 2. PLIs and BER estimation model used to evaluate the signal quality are also given in this chapter. In Chapter 3, the formal definition of the problem, and previous studies related to the subject of this thesis are given. In Chapter 4, the effects of IM in MLR networks are evaluated and proposed six IM-based approches are explained. Proposed approaches are compared with one another and the algorithms without IM. In Chapter 5, two novel approaches proposed for IA lightpath provisioning are discussed.

The performances of the proposed approaches are compared with other PLI-aware MLR lightpath provisioning algorithms. In Chapter 6, we present the effects of launch power on signal quality. Two approaches to determine appropriate launch power in MLR networks are discussed. The performances of proposed launch power determination approaches are compared with existing approaches. Chapter 7 concludes the thesis.

2. OPTICAL WDM TRANSMISSION

2.1 Introduction

In optical Wavelength Division Multiplexing (WDM) networks, the optical transmission spectrum is carved up into a number of non-overlapping wavelength channels on which each channel can carry a single communication (Figure 2.1(a)). End users communicate with one another via WDM channels, which are referred

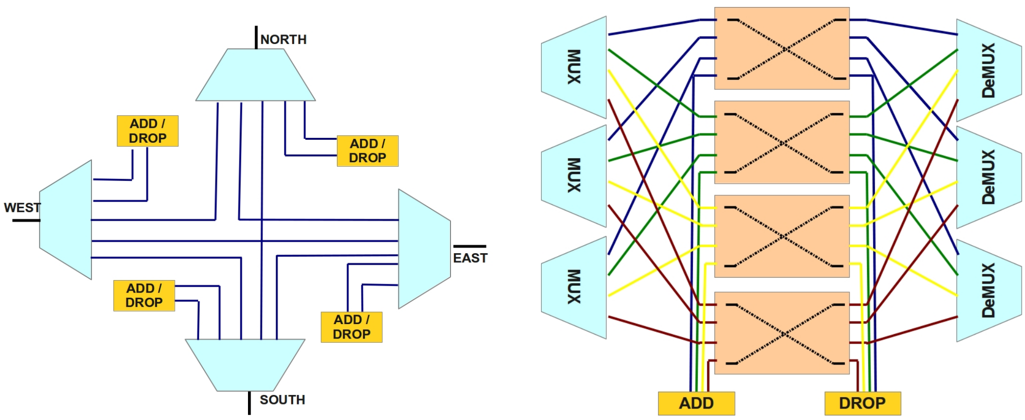


(a) Lightpaths at different wavelengths. (b) Different line rates sharing the same link.

Figure 2.1: MLR on WDM optical networks.

to as lightpaths [2]. Modulated signals are put on the channels from one end by a laser transmitter (TX) to be received by the receivers (RX); those are tuned to the same wavelength at the other end of the communication channel (Figure 2.1(a)). Each channel may transport different types of traffic, such as SONET/SDH over one wavelength, ATM over another, and TDM voice, video or IP over another, using the same infrastructure. In opaque networks, data transmission occurs over point-to-point links so that the signal is regenerated at every intermediate node along transmission channel. The regeneration of optical signal is done using optical-electronic-optical (OEO) conversion. In translucent architecture, regenerators are placed sparsely. It eliminates much of the electronic process and allows a signal to remain in the optical domain as much as it can. In transparent networks, the transmission occurs in optical domain. The optical channels are not processed at intermediate nodes. The number of wavelengths, which each fiber can carry simultaneously, is limited by the physical characteristics of the fiber and the optical technology used. WDM makes it possible to transfer data at different bit rates, over different channels on the same link (Figure 2.1(b)), which is called *Mixed (or Multi) Line Rate* (MLR) [7, 8]. The terms *Optical Network* and *Optical WDM Network* are used interchangeably throughout this thesis.

An *Optical Network* consists of optical nodes interconnected with fiber links. Optical networks are conceptually segmented in three as: Access, metro, and core/backbone networks. The access segment of the network refers to the portion between customer location and its central office. Interconnected central offices constitute metro areas for carriers. The backbone segment interconnects metro segments. In optical backbone networks, single mode (SM) fibers and intermittently placed in-line amplifiers are used for connecting nodes, called reconfigurable optical add-drop multiplexers (ROADM). Figure 2.2 shows the architecture of two different broadly used ROADM types.



(a) Degree-4 WSS Node [9]. (b) 3×3 OXC with 4 wavelengths.

Figure 2.2: Different node types.

A **Wavelength Selective Switch (WSS)** ROADM (Figure 2.2(a)) consists of WSS, channel monitor, and amplifier. WSS is a device that extracts and inserts the light. WSSs use Fiber Bragg Gratings (FBG) to separate the wavelengths. FBGs are prism like devices that separate the light into component colors. WSS uses different switching technologies to select the frequency. Currently, the two major switching technologies are micro electro mechanical systems (MEMS) and liquid crystals (LCoS). Channel monitors continuously monitor the optical power level of wavelengths.

An **Optical Cross Connect (OXC)** switches optical signals from input ports to output ports. It consists of demultiplexers (DeMUX), optical switches, and multiplexers (MUX) (Figure 2.2(b)). In order to route each wavelength separately, each input fiber is connected to demultiplexers which spatially separate the wavelengths on the fiber. A typical $n \times n$ OXC connects n input fibers, each carrying W different wavelengths to n output fibers using W optical switches, each for one wavelength. Each wavelength is switched accordingly, and all the wavelengths going through the same output port are multiplexed on to the output fiber. The optical switch can have strictly nonblocking active-splitter active-combiner architecture [10].

In ROADM systems, the flexibility of the mesh network is extended by Colorless, Directionless, and Contentionless features of optical nodes. Colorless feature at an add/drop port is the ability of tunable transponders to have transparent wavelength access to all WDM network ports. Directionless feature is ability of tunable transponders to have non-blocking access to all ports. Contentionless is ability to avoid contention.

The optical signal loses its power along the path it travels. **Optical Amplifiers** make long distance optical transmission possible by providing a power boost to the signals. Optical signal is not converted into the electrical domain but its power is increased. Erbium-Doped Fiber Amplifiers (EDFA) are commonly used, where the channels on the fiber are required to be amplified. The part of a link between amplifiers is called a *span*, and its length is nearly 80 km. The main disadvantage of an EDFA is the noise it adds to the signal. The noise at an EDFA is spontaneous emission, thus it is called amplified spontaneous emission (refer to Section 2.2.1).

2.1.1 Transmission of a signal

Wave Theory describes light as an electromagnetic wave. Electromagnetic waves have four basic properties: *intensity*, *wavelength* (or *frequency*), *polarization*, and *phase*. For ideal conditions, these properties for an optical carrier are constant, except for modulation.

Intensity can be referred to as power of the optical carrier. It is a measure of the energy flux (rate of transfer of energy through a surface), averaged over a certain time period. To find the intensity, energy density (that is, the energy per unit volume) multiplid by the velocity at which the energy is moving. The resulting vector has the units of power divided by area (i.e., W/m^2). Greater intensity means more photons but the energy of each is exactly the same.

Polarization describes the orientation of oscillations for waves. The polarization of light is described by specifying the orientation of the wave's electric field at a point in space over one period of the oscillation. The **phase** of a wave is the fraction of a complete cycle corresponding to an offset in the displacement from a specified reference point at time t = 0.

The **wavelength** (λ) is the spatial period of a sinusoidal wave, the distance over which the wave′s shape repeats. The frequency is the number of oscillations per second. Wavelength is inversely proportional to the frequency of a sinusoidal wave moving

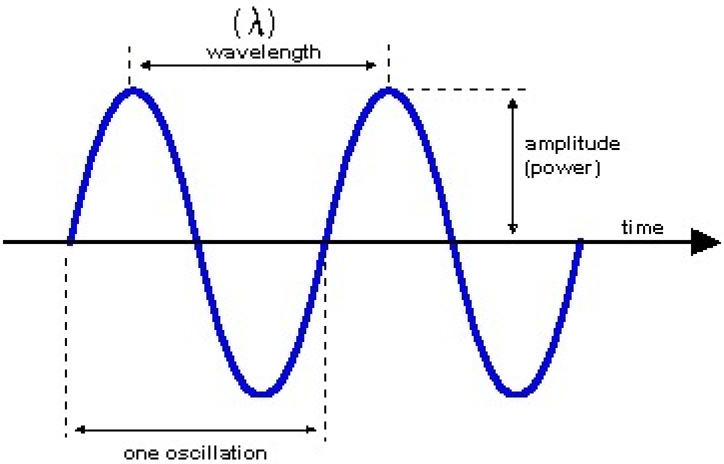


Figure 2.3: Wavelength and frequency relation.

at a fixed wave speed; waves with higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths. The wavelength λ of a sinusoidal light traveling at constant speed is given by:

$$\lambda = \frac{c}{f} \tag{2.1}$$

where c is the velocity of light ($3 \times 10^8 m/s$), f is the frequency (hertz), and λ is the wavelength (meters). The speed of light in fiber is nearly $2 \times 10^8 m/s$, and the wavelengths are correspondingly different. Frequency or wavelength terms can be used to characterize an optical WDM signal. Wavelength is measured in units of nanometers (nm) or micrometers (μm or microns). In WDM networks, a fiber carries a number of optical signals simultaneously in or around C-band (1530-1565 nm). These optical signals must obviously be at different carrier wavelengths. Thus, it is convenient to refer to the available bandwidth as a set of channels. Each optical signal is allotted a distinct channel, and each channel has sufficient bandwidth to accommodate the modulated signal. In order to avoid interference between different optical signals, each channel is separated from the other channels by a certain minimum bandwidth called *channel spacing*. Channel spacing is also measured in units of wavelengths or frequencies. The relationship between the frequency spacing Δf and the wavelength spacing $\Delta\lambda$ is given as [11]:

$$\Delta f = \frac{c}{\lambda_0^2}\Delta\lambda \tag{2.2}$$

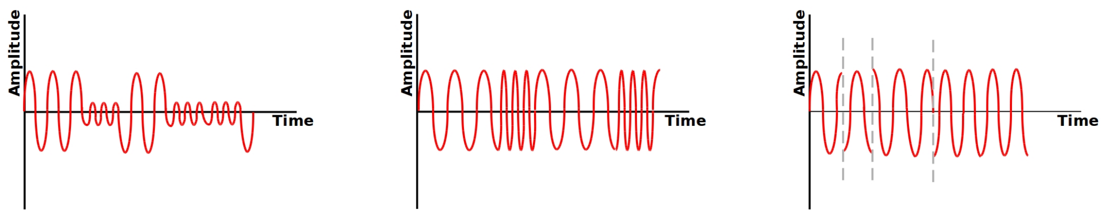
Wavelength spacing of 0.8 nm corresponds to a frequency spacing of 100 GHz, at wavelength λ_0 = 1550 nm.

2.1.2 Modulation

Modulation is the process of encoding an electrical signal onto the carrier. The optical carrier wave is formulated as [12]:

$$\mathbf{E}(t) = \hat{e}Acos(\omega_0 t + \varphi) \tag{2.3}$$

where $\mathbf{E}$ is the electric field vector, $\hat{e}$ is the polarization unit vector, A is the amplitude, ω_0 is the carrier frequency, and φ is the phase. Thus, it is possible to choose one of the variables to modulate a signal: amplitude, frequency, or phase. The modulation techniques are called amplitude-shift keying (ASK) (Figure 2.4 (a)), frequency-shift keying (FSK) (Figure 2.4 (b)), and phase-shift keying (PSK) (Figure 2.4 (c)), depending on whether the amplitude, frequency, or phase is modulated.



(a) ASK (b) FSK (c) PSK

Figure 2.4: Different keying techniques.

Amplitude Shift Keying is the simplest and the most common technique, which consists of changing the signal power (intensity) between two levels, 1 and 0 levels. The laser used for transmission is either *on* or *off* depending on the value of the signal;

therefore it is also called On-Off Keying (OOK) [12]. The information can be coded in two symbols 0 and 1, using only the amplitude. OOK is commonly used for lower ($\leq$10G) transmission rates.

Capacity and flexibility of optical networks can be increased using higher line rates ($\geq$40G). Using amplitude modulation for high line rates increases the requirement for bandwidth. Higher bandwidth results in linear increase at the noise power level of the communication channel. Increased noise results in shorter optical reach, and more regenerators for longer distances. Increasing the laser power will not work because of increasing non-linear effects. Thus, channel bit rate can be increased using advanced modulation formats.

Phase Shift Keying is the modulation using the phase of the signal. This can be achieved simply by defining a relative phase shift from the carrier. Phase modulation is used for higher line rates.

Quadrature Phase Shift Keying is a form of PSK in which two bits are modulated at once, selecting one of four possible carrier phase shifts (0, $\pi/2$, π, $3\pi/4$).

Differential Quadrature Phase Shift Keying (DQPSK) encodes information in the differential optical phases ($\Delta\phi$) between successive bits, where $\Delta\phi$ may take one of four values [0, $\pi/2$, π, $3\pi/4$]. Since each symbol transmits two bits of information, the symbol rate is half of the total bit rate. Spectral efficiency of this modulation technique makes it suitable to carry 40 Gbps channels [13].

Dual Polarization-Quadrature Phase Shift Keying (DP-QPSK) decomposes a signal into two polarizations of the same frequency at 90° from each other in order to avoid mutual interaction as they are being launched into the fiber. One signal is transmitted in the horizontal polarization and the other in the vertical polarization. These two signals can be combined or split up using an optical polarization beam splitter. By combining the effects of dual polarization and DQPSK, we can have four bits per symbol: one from each polarization and two from QPSK. This makes DP-QPSK suitable for 100 Gbps [5], and within the bandwidth requirements of existing WDM grid.

2.2 Physical Layer Impairments (PLI)

The PLIs can be classified into two categories: linear and non-linear [1]. Linear effects are static in nature, and they are independent of signal power. They affect each wavelength individually. Their effects on end-to-end lightpaths can be estimated using link parameters; hence, linear impairments can be handled as a constraint on routing or other optical WDM network problems. Non-linear effects, on the other hand, are dynamic in nature and are more complex because they not only affect each optical channel individually but also cause disturbance and interference between them.

The PLIs can also be classified according to the scope of the effects, such as single-channel effects and inter-channel (or multi-channel) effects. The single-channel effects can be estimated using the channel (bit rate, wavelength, modulation format, etc.) and the path characteristics (fiber loss, chromatic dispersion, amplifiers power, etc.). On the contrary, the inter-channels effects depend not only on the channel and path parameters, but also on other lightpaths deployed in the network at the specific time. The single and inter-channel impairments are summarized in Table 2.1.

Table 2.1: Single and inter-channel impairments.

Physical-layer impairments	**Single-channel effects**	**Inter-channel effects**
Linear Impairments	Attenuation, CD, ASE, Insertion Loss, PMD	XT
Non-Linear Impairments	SPM, SBS, SRS	XPM, FWM

2.2.1 Linear impairments

Attenuation is the decrease in power of an optical signal as the signal travels along the path (Figure 2.5). When determining the maximum distance that a signal can be sent for a given transmitter power and receiver sensitivity, attenuation must be considered. Receiver sensitivity is the power required by a receiver to detect a signal. Let $P(L)$ be the power of the optical pulse at distance $L\,(km)$ from the transmitter, and let α be the attenuation (loss) constant of the fiber (dB/km). Attenuation is characterized in [1] by:

$$P(L) = 10^{\alpha L/10} P_{in} \quad \textbf{(2.4)}$$

where P_{in} is the signal power at transmitter. To keep the power of signal within the acceptable range, optical amplifiers are intermittently placed in the optical networks.

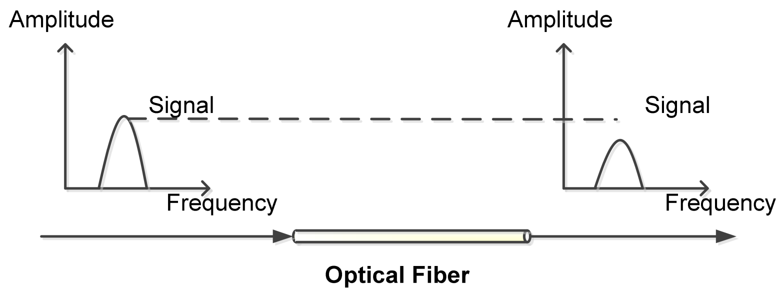


Figure 2.5: Attenuation of optical signal.

Amplified spontaneous emission (ASE) is the noise produced by optical amplifiers. This noise accumulates as the amplifiers cascade along the lightpath. ASE noise occurs in both the forward and reverse directions, as shown in Figure 2.6. Forward ASE is a direct concern to system performance because that noise will co-propagate with the signal to the receiver. Backward ASE can lead to degradation of incoming signal power, which can easily be compensated.

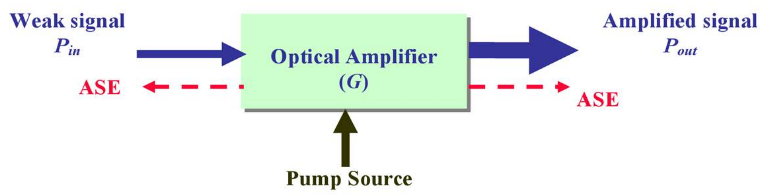


Figure 2.6: ASE noise production.

ASE noise is one of the major contributors to the total optical noise for long haul transmission systems. ASE noise power measured over a given spectral bandwidth B_0 can be calculated using the following formula [11]:

$$P_{ASE} = 2n_{sp}.h.f.B_0(G-1) \quad \textbf{(2.5)}$$

where	P_{ASE}	:	Average amplifier ASE noise power, W
	n_{sp}	:	spontaneous emission factor (or population inversion parameter)
	h	:	Plank's constant 6.626069×10^{-34}js
	f	:	center frequency, assuming 193.30 THz (1552.12 nm)
	B_0	:	Optical channel bandwidth
	G	:	Gain of amplifier

Dispersion is the time-domain spreading or widening of a pulse duration as it travels through a fiber. As a pulse gets wider, its shape changes. Dispersion limits the bit spacing and the maximum transmission rate on an optical channel. Too much dispersion in the network leads to degradation of signal quality and loss of data. On the other hand, having zero dispersion leads to non-linear impairments (i.e., FWM) in WDM networks.

Optical pulse has different components (wavelength, polarization state). The difference in velocity caused by wavelength is called **chromatic dispersion**, and the difference in velocity caused by different polarization modes is called **polarization mode dispersion**.

Polarization Mode Dispersion (PMD) occurs when two different polarizations of light in a waveguide, which normally travel at the same speed, travel at different speeds due to birefringence (double refraction) effect of light. Birefringence is a property of optical materials for which light, polarized along the x axis, experiences a different index of refraction, and travels at a different speed than does light polarized along the y axis. PMD causes inter-channel-interference (ICI), as shown in Figure 2.7.

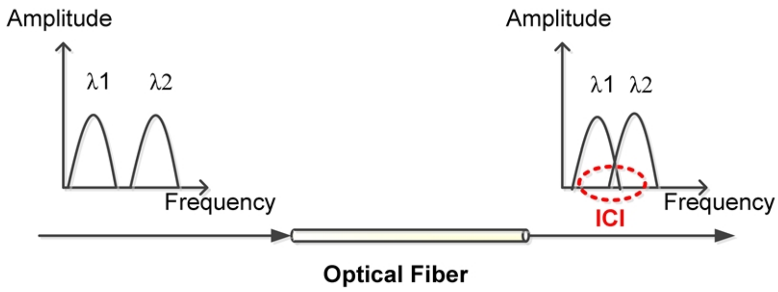


Figure 2.7: PMD effect on channels of fiber.

PMD becomes a problem for higher rates (≥40G), and long distances. On a transparent transmission, PMD effect can be evaluated using the following formula [14]:

$$B \times \sqrt{\sum_{k=1}^{M} D_{PMD}^{2}(k) \times L(k)} \leq \delta \qquad \textbf{(2.6)}$$

where B is the bit rate, transparent segment of the lightpath consists of M spans, and k^{th} span has length of $L(k)$. $D_{PMD}(k)$ represents the PMD coefficient of the k^{th} span, which is measured in $ps/\sqrt{km}$. The parameter δ represents the fractional pulse broadening caused by PMD, which is typically less than 10% of a bit's time slot for which the PMD can be tolerated [1]. PMD values vary from fiber to fiber in the range of 0.01-10 $ps/\sqrt{km}$ [15].

Chromatic Dispersion (CD) is pulse spreading due to the fact that different wavelengths of light propagate at slightly different velocities through the fiber.

Chromatic dispersion can be defined as the frequency dependence of the refractive index n_f. When an electromagnetic wave interacts with the bounds of transmission medium, the response of the medium differs depending on the optical frequency f. It yields pulse broadening, which accumulates along the path. CD induces inter-symbol interference (ISI), as shown in Figure 2.8. Chromatic dispersion is deterministic and

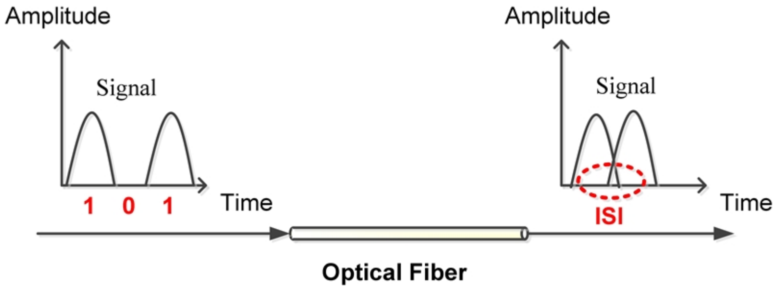


Figure 2.8: Effects of chromatic dispersion.

linear. It is not affected by the environment. Thus, it can be predicted and compensated. Dispersion compensating fibers (DCF) have negative dispersion (i.e., -85 ps/nm.km) to compensate the positive dispersion of standard single mode fiber (SSMF). But compensation is made for only the center channel of the band of wavelengths. Other WDM channels are left with residual dispersion. So, WDM network design requires knowledge of end-to-end CD as a function of wavelength, especially for long distances.

Insertion Loss is introduced by the optical components, such as couplers, filters, multiplexers/demultiplexers, and switches. It is usually independent of wavelength. Loss amount at a switch is dependent upon the number of switching elements that a signal must pass through. A $P \times P$ switching element is composed of $1 \times P$ active splitting elements and $P \times 1$ active combining elements, in which basic building block is a 2×2 crossbar switch. The active splitter half of the $P \times P$ switch consists of $\log_2 P$ stages of 1×2 elements, and similarly combiner half of the $P \times P$ switch consists of $\log_2 P$ stages of 2×1 elements. In this architecture, all signals have to pass through the same number ($2\log_2 P$) of individual switch elements. Each switch element has a characteristic loss, L_s in dB, associated with it. An additional attenuation occurs during the on-off transfer process of the signal. This waveguide/fiber coupling loss is represented by L_w and includes the reflection losses and mismatch losses. Thus insertion loss of $P \times P$ switch is given by [10]:

$$2\log_2 P L_s + 4L_w \tag{2.7}$$

Crosstalk (XT) is signal noise, which occurs due to the non-ideal isolation of demultiplexers, switching elements and multiplexers inside an OXC. It is the leakage from neighboring wavelength or same wavelength at different input port. Linear crosstalk depends on the ratio of the optical powers of two channels. There are two different types of switch crosstalk: intraband and interband crosstalk. Due to non-ideal isolation of the switching element of OXC, lightpaths crossing the same node over same wavelength of actual lightpath incur some noise, called intraband crosstalk (see Figure 2.9 (a)). It cannot be removed by optical filters and therefore accumulates through the network. Also the neighboring lightpath coming from the same input of the OXC with adjacent wavelengths induce some noise, referred to as interband crosstalk (see Figure 2.9 (b)). The crosstalk noise power of each OXC can be formulated as

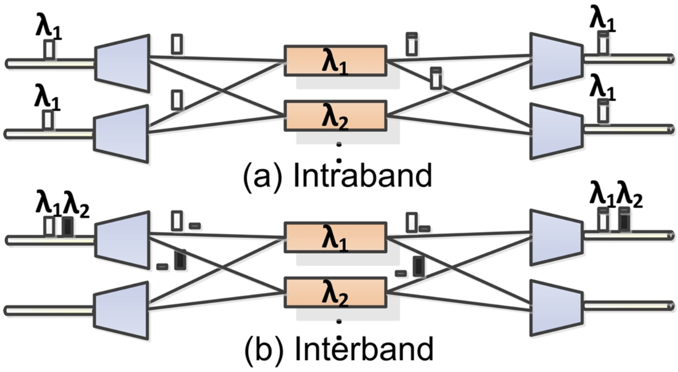


Figure 2.9: Switch crosstalk types.

follows [10]:

$$XT_{k,\lambda} = \sum_{n=1}^{N} XT_{sw} P_k \nu_{\lambda,n} + XT_{dmx} P_k \nu_{\lambda \mp 1} \quad \textbf{(2.8)}$$

where N is the input port number, P_k is the signal power of affecting port at the given node. XT_{sw} and XT_{dmx} account for isolation factor of switch and dumultiplexer, respectively. $\nu_{\lambda,n}$ and $\nu_{\lambda \mp 1}$ are binary variables indicating the existence of the related interband and intraband crosstalk. First part of the equation gives the total crosstalk caused by the lightpaths which have the same wavelength. The last part of the equation gives the crosstalk caused by the signals from the same input port, due to non-ideal demultiplexer isolation. Considering gains and losses along the lightpath, accumulated crosstalk power at the destination node $(k+1)$ can be calculated recursively using the approach given in [10]:

$$P_{XT}(k+1,\lambda) = P_{XT}(k,\lambda)L_f(k,k+1)G_{in}(k+1,\lambda) .L_{dm}(k+1)L_{sw}(k+1)L_{mx}(k+1)G_{out}(k+1,\lambda)L_{tap}^2 +XT_{k,\lambda} \quad \textbf{(2.9)}$$

where L_x indicates the loss values of different components, and G_{in} and G_{out} indicate the gain values due to pre/post-amplifiers.

2.2.2 Non-linear impairments

The non-linear impairments in optical fiber occur due to either change in the refractive index of the medium with optical intensity (power) or stimulated scattering [3].

Stimulated scattering arises due to the interaction of light waves (optical signals) with photons (molecular vibrations) in the silica medium. This leads to intensity dependent gain or loss. The two main effects in this category are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). SBS occurs when an optical signal in fiber interacts with the density variations (such as thermally driven density fluctuations and acoustic phonons) and changes its path. Raman scattering arises from the interaction of light with the vibrational modes of the constituent molecules in the scattering medium; equivalently this can be considered as the scattering of light from optical phonons. SRS and SBS are quite similar non-linear effects. The main difference between the two is that optical phonons participate in SRS, while acoustic phonons participate in SBS.

Another set of non-linear effects arises due to the dependence of the refractive index on the intensity of the applied electric field, which is called *Kerr Effect*. There are three different main categories of this effect: Self-phase modulation, cross-phase modulation, and four-wave mixing. Increasing WDM channel capacity, decreasing channel spacing, and increasing optical power increase these non-linear effects.

Four-Wave Mixing (FWM) is interaction between three wavelengths that produces a 4th wavelength. In a WDM system using the angular frequencies $\omega_1, \omega_2, ...\omega_n$, the intensity dependence of the refractive index not only induces phase shifts within a channel but also gives rise to signals at new frequencies such as $2\omega_i - \omega_j$ and $\omega_i + \omega_j - \omega_k$. This phenomenon is called four-wave mixing. Four-wave mixing effect is independent of the bit rate but is critically dependent on the channel spacing and fiber chromatic dispersion. Decreasing the channel spacing increases the four-wave mixing effect, and so does decreasing the chromatic dispersion.

Self-Phase Modulation (SPM) is the non-linear interaction of a channel with itself. The Kerr Effect of a fiber leads to a phase shift of an optical signal due to its own intensity. The refractive index of the silica, n, increases with the optical power, P:

$$n = n_0 + n_2 \frac{P}{A_{eff}} \tag{2.10}$$

where n_0 is the linear refraction index at low powers, and A_{eff} is the effective area of optical mode in the fiber (typical single-mode fibers is 50-80 μm). The coefficient n_2 is typically ~2.6 x 10-20m^2/W in standard single-mode fiber [16]. Variations in the power of an optical signal result in variations in the phase of the signal. Instantaneous variations in a signal's phase will result in instantaneous variations of the frequency around the signal's central frequency. In the frequency domain, this effect can be seen as a spectral broadening of a signal. For very short pulses, the additional frequency components generated by SPM combined with the effects of chromatic dispersion also lead to spreading or compression of the pulse in the time domain, affecting the maximum bit rate and the BER. Optical phase shift $\Delta\phi_{SPM}$ results after propagation over distance L is given by [16]:

$$\Delta\phi_{SPM} = \gamma.P.L_{eff} \tag{2.11}$$

where γ is the fiber non-linear coefficient, and defined as: $\gamma = \frac{n_2 \omega_0}{c A_{eff}}$. ω_0 is the optical carrier frequency of the pulse, c is the speed of light. The effective length, L_{eff} takes the fiber loss, α into account, and is defined as:

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \tag{2.12}$$

Cross-Phase Modulation (XPM) is a shift in the phase of a signal caused by the change in intensity of a signal propagating at a different wavelength. XPM can lead to asymmetric spectral broadening, and combined with SPM and dispersion may also affect the pulse shape in the time domain. In XPM, the phase of the signal in one channel is altered by the intensity fluctuations of the other channels. Its impact of XPM depends on the modulation format, power and transmission rate of the involved signals. Several approaches based on analytical approximations have been investigated [4, 17–19]. We will go with the simplified model used in [19], in this thesis. The noise contribution of an interfering OOK signal j to channel i is given as [19]:

$$\sigma_{i,j}^2 = \frac{\phi_{i,j}^2 \tau_{i,j}}{T_j} \left\{ \frac{K+1}{K} c_1 - \frac{c_2}{K^2} \sum_{h=1}^{K} h \exp\left(-\frac{hT}{\tau_{i,j}}\right) - \frac{1}{K^2} \sum_{h=1}^{K'} h c_3(h) \right\} \qquad \textbf{(2.13)}$$

where $\phi_{i,j}$ is the phase shift, $\tau_{i,j}$ is the group delay of channel j with respect to channel i, K is the filtering effect, T is symbol time, and T_j is the pulse width. c values give the spectral shape of the OOK channel. $\tau_{i,j}$,K', c_1, c_2, and c_3 are given as:

$$\begin{aligned} \tau_{i,j} &= \frac{\left|D_i \Delta\lambda_j\right|}{\alpha_i} \\ K' &= \lceil T_j/T \rceil - 1 \\ c_1 &= \exp\left(-\frac{T_j}{\tau_{i,j}}\right) + \frac{T_j}{\tau_{i,j}} - 1 \\ c_2 &= 2\left[\cosh\left(\frac{T_j}{\tau_{i,j}}\right) - 1\right] \\ c_3(h) &= 2\left[\sinh\left(\frac{hT - T_j}{\tau_{i,j}}\right) - \frac{hT - T_j}{\tau_{i,j}}\right] \end{aligned} \qquad \textbf{(2.14)}$$

The phase shift $\phi_{i,j}$ induced on channel i by channel j due to XPM is given as:

$$\phi_{i,j} = \frac{2\gamma_i . P_{i,j}}{\alpha_i} \qquad \textbf{(2.15)}$$

where γ is the fiber non-linear coefficient, α is the attenuation coefficient, and $P_{i,j}$ is the power of the interfering channel j.

2.3 Quality of Transmission (QoT)

Along the transparent optical path, a signal undergoes various PLIs and its quality degrades as it travels through optical components. The receiver makes decision about the transmitted bit whether it is 1 or 0, and it could make a wrong decision due to low signals quality. So it is necessary to evaluate the signal quality at the receiver side.

BER is an appropriate criterion to decide the quality of the signal. It is the probability of incorrect decision of a bit by the decision circuit of the receiver. Actually, BER value is not available before the lightpath is set up. Even calculating BER value instantaneously is not easy. A 10^{-12} BER means that one bit is received in error for every terabit of transmitted data bits. It will take days to get reasonable sampling data. Thus, BER is estimated using the statistical and analytic models of physical-layer impairments, those taken into consideration. MLR networks adopt different modulation schemes, and each modulation scheme requires different BER evaluation models.

OSNR is the ratio between the total signal power and the noise power on the reference bandwidth.

2.3.1 Optical signal-to-noise ratio (OSNR)

OSNR is the strength of the signal compared to the level of noise. It is used to evaluate the power of signal and the power of noise over specific bandwidth.

$$OSNR = \frac{P_{received}}{N_{linear} + N_{non-linear}} \quad \textbf{(2.16)}$$

where $P_{received}$ denotes the signal power at the receiver, and N_{linear} and $N_{non-linear}$ denotes the undesired linear and non-linear noise power accumulated along the path.

For a given lightpath from source to destination, output power of signal (P_{out}) is ruined with three main noise components: the inline amplifiers noise, node noise, fiber noise. Node noise includes switch crosstalk, and ASE noise of EDFA amplifiers. A node also has other loss sources that affect the OSNR, such as demultiplexer (L_{dmx}), multiplexer (L_{mx}), tap (L_{tap}), and switching element (L_{sw}). Besides, the signal is amplified to a certain power level before (G_{in}, pre-amplification), and after it is switched (G_{out}, post-amplification). Optical amplifier noise (N_{ASE}) and FWM are the noise factors on the fiber. Noise factors within the node are $N_{ASE}, XT_{DMX}, XT_{MX}, XT_{SW}$, losses induced by components ($L_{dmx}, L_{mx}, L_{tap}, L_{sw}$), and the amplifier gains (G_{in}, G_{out}).

In order to evaluate linear and non-linear noise factors, we employed the staged OSNR model as in Equation 2.17 [11]:

$$1/OSNR = \sum 1/OSNR_{stages} \quad \textbf{(2.17)}$$

Since the OSNR on a lightpath varies, an iterative method based on the current network state is needed to calculate the signal and noise powers propagating through the lightpath. The output noise power (N_{out}) of $(k+1)^{th}$ stage can be considered iteratively as:

$$\begin{aligned}N_{out}(k+1) &= N_{out}(k)\frac{G(k,\lambda).e^{-\alpha d_k}}{L_{dmx}L_{sw}L_{mx}} \\ &+\frac{G(k,\lambda)e^{-\alpha d_k}}{L_{dmx}L_{sw}}\frac{hv(\lambda)B_0}{2} \\ &\times\left(F_{amp_k}+\frac{F_{amp_k}}{e^{-\alpha d_k}G(k,\lambda)}\right) \\ &+\frac{G(k,\lambda)}{L_{sw}L_{mx}}\sum_{j=1}^{m}P_{FWM_k}(\lambda) \\ &+\varepsilon\sum_{j=1}^{s}P_{sw_{k+1,j}}(\lambda) \end{aligned} \quad \textbf{(2.18)}$$

The output signal power of $(k+1)^{th}$ stage is:

$$P_{out}(k+1) = P_{out}(k)\left(\frac{G(k,\lambda).e^{-\alpha d_k}}{L_{dmx}L_{sw}L_{mx}}\right) \quad \textbf{(2.19)}$$

2.3.2 Bit-error rate (BER) estimation

BER differs according to modulation formats.

OOK modulation is affected mostly by ASE, CD, PMD, and SPM. BER can be approximated for OOK modulated signals as [19]:

$$BER \approx \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}} \quad \textbf{(2.20)}$$

where Q-factor is related to signal to noise ratio as:

$$Q = \frac{2\rho}{\sqrt{M}+\sqrt{M+4\rho}} \quad \textbf{(2.21)}$$

where $M = 2B_0T$, B_0 is the optical filter bandwidth, and T is the symbol time. The relation with OSNR is as:

$$\rho = nB_{ref}T.OSNR \quad \textbf{(2.22)}$$

where B_{ref} is the reference bandwidth, n is the ratio between number of noise and signal polarizations.

DQPSK modulation is commonly used for 40 Gbps transmission [18]. Most detrimental impairments for this type of modulation are ASE, CD, PMD, SPM, and XPM [19]. Especially, when a signal is transmitted adjacent to an OOK channel, XPM becomes the most detrimental effect on this signal. BER estimation for this modulation can be approximated as [19]:

$$BER = \frac{3}{8}-\frac{\rho}{4}e^{-\rho}\sum_{m=1}^{\infty}\left[I_{\frac{m-1}{2}}\left(\frac{\rho}{2}\right)+I_{\frac{m+1}{2}}\left(\frac{\rho}{2}\right)\right]^2\times\frac{sin(m\pi/4)}{m}e^{-m^2\sigma_{NL}^2/2} \quad \textbf{(2.23)}$$

where $I_k(x)$ is the k-order modified Bessel function of the first kind. ρ is the signal to noise ratio and related to OSNR through Equation (2.22). Variance of non-linear phase noise is given as:

$$\sigma_{NL}^2 = \sigma_{SPM}^2 + \sigma_{XPM}^2 \tag{2.24}$$

SPM contribution of phase noise is approximated as:

$$\sigma_{SPM}^2 \approx 4\phi_{SPM}^2/(3\rho) \tag{2.25}$$

ϕ_{SPM} is discussed in section 2.2.2. σ_{XPM}^2 is given detailed in Equation (2.13).

DP-QPSK is the candidate modulation for 100G line rates [4]. DP-QPSK is also affected by ASE, CD, PMD, SPM, and XPM [19]. OOK neighboring channels have detrimental XPM effect on DP-QPSK channels. BER estimation for this modulation can be approximated as [19]:

$$BER = \frac{3}{8} - \frac{1}{2}\sqrt{\frac{\rho}{\pi}e^{-\rho/2}}\sum_{m=1}^{\infty}\left[I_{\frac{m-1}{2}}\left(\frac{\rho}{2}\right) + I_{\frac{m+1}{2}}\left(\frac{\rho}{2}\right)\right] \times \frac{sin(m\pi/4)}{m}e^{-m^2\sigma_{NL}^2/2} \tag{2.26}$$

SPM contribution of phase noise for this modulation is approximated as:

$$\sigma_{SPM}^2 \approx 2\phi_{SPM}^2/(3\rho) \tag{2.27}$$

Gaussian Approximation: In QPSK systems, errors occur when the received signal phase is different from transmitted one by more than $\pi/4$. With the assumption of phase noise being Gaussian, phase rotation induced by noise exceeds a given value (θ) approximately by $Q(\sqrt{2\rho}\sin\theta)$. Using this information, it is possible to use BER evaluation model given in Equation (2.20), instead of Equations (2.23) and (2.26) with the following formula for Q-factor [19]:

$$Q = \frac{\pi/4}{\sqrt{\frac{S}{2\rho}(\frac{\theta}{\sin\theta})^2 + \sigma_{NL}^2}} \tag{2.28}$$

where S stands for effected term number (1 and 2 respectively, for QPSK and DP-QPSK). θ is used as ([19]):

$$\theta = (\pi/4)/(S + 2\rho\sigma_{NL}^2) \tag{2.29}$$

Guard Band (GB) is the number of wavelengths between two lightpaths, beyond which the effect of a lightpath on the other can be neglected. GB is obtained from the minimum spectral separation value that guarantees to have negligible detrimental effects (e.g., noise less than 0.1 dB) induced by neighboring lightpaths. The spectral separation of channel i from affecting channel j can be found using following formula [20]:

$$\Delta\lambda_{GB} > \sqrt{160\rho T_j T gD(K) \sum_i \frac{\gamma_i^2 P_{i,j}^2}{D_i^2}} \quad \textbf{(2.30)}$$

where ρ is the signal to noise ratio and related to OSNR through Equation (2.22), K is the filtering effect due to differential detection in phase shift keying modulation formats. $gD(K)$ is differential or coherent detection with phase estimation and for large group delays it is defined as [20]: $gD(K) = \frac{2K+3+(1/K)}{6}$.

Optical Power and Loss: In optical communication, decibel units (dB) are used to measure the power and signal levels. Logarithmic decibel units are used to represent relative values, instead of absolute values. The standard reference value for optical communication is 1 milliwatt (mW) [11]. Suppose the transmitted signal has power of P watts (W). In terms of dBm units, it is denoted as [3]:

$$P_{dBm} = 10log\left(\frac{P_{mW}}{1mW}\right) \quad \textbf{(2.31)}$$

For example, a power of 1 mW corresponds to 0 dBm and 1μW corresponds to -30 dBm. A power of 5 mW corresponds nearly to 7 dBm.

As the signal propagates through the fiber, its power decreases due to loss occurred at optical components and attenuation on fiber. The loss ratio, T_r is defined as:

$$LossRatio = T_r = \frac{P_{out}}{P_{in}} \quad \textbf{(2.32)}$$

where P_{out} and P_{in} are fiber or component output and input powers at a specific wavelength, respectively. Loss ratio is always less than or equal to 1. If P_{out}/P_{in} ratio is greater than 1, than it is referred to as *gain*.

The *optical loss* represented with logarithmic scale value is standardized in dB units. Since T_r is always less than 1, then the *optical loss* is represented as a positive number or 0:

$$(\alpha)_{dB} = -10\,log\,T_r = -10\,log\left(\frac{P_{out}}{P_{in}}\right) \quad \textbf{(2.33)}$$

As an example, if P_{in} is 1 mW and measured receiver power (P_{out}) is 0.05 mW, the optical loss value would be:

$$\alpha = -10\,log\left(\frac{0.025}{1}\right)$$
$$\alpha = 13.01\,dB.$$

In this context, a signal being attenuated by a factor of 1000 would equivalently undergo a 30 dB loss.

The optical loss for fiber link is usually measured per km (dB/km). So, for example, a signal traveling through 120 km of fiber with a loss of 0.25 dB/km would be attenuated by 30 dB.

The minimum power requirement of the receiver is called the *receiver sensitivity*, (R). We must ensure that the transmit power is high enough so that it can maintain *signal power* > R at the receiver end. That does not mean that we can increase the transmit power as much as we want to send bits across long distances. High input power causes more non-linear impairments. In addition, an upper acceptable signal power limit exists for every receiver. Therefore, the maximum input power that we can launch into the fiber, thus the reach is limited.

3. IMPAIRMENT-AWARE LIGHTPATH PROVISIONING IN MLR NETWORKS

3.1 Introduction

Impairment-aware (IA) lightpath provisioning is a cross-layer optimization problem which aims to maximize the established connections at the network layer, while assuring signal quality at the physical layer.

In MLR networks, advanced modulation techniques (e.g., DQPSK, DP-QPSK) are used for high line rates. On the other hand, DQPSK and DP-QPSK modulated signals are highly susceptible to PLIs; therefore we have to take into account the trade-off between capacity and signal quality. Accounting for PLIs during the provisioning phase, which is an important problem in single-line-rate WDM networks, acquires even larger importance in MLR networks. In MLR networks, the problem has two new dimensions: the disruptive interaction of different modulation formats, and the trade-off between capacity and optical reach.

We first investigate the effects of inverse multiplexing (IM), which is a technique that tries to exploit the advantage of transmitting the signals with low line rates, where the high line rate is not possible due to impairments. The network layer applications enable to inversely multiplex the connection requests with high line rates into smaller line rates at the source node, propagate them separately over a transparent MLR network, and then combine them back at the destination node. We propose various IM-based schemes to account for the IA dynamic lightpath provisioning problem in MLR optical networks. The proposed schemes use three different path-selection algorithms: shortest path (SP), minimum hop (MH) path, and least congested path (LCP). We employed two different wavelength-assignment schemes with each path-selection algorithms: Best-BER (BB) and maximum spectral distance (MSD).

We also propose two novel schemes for dynamic lightpath provisioning in MLR networks which consider various linear and non-linear impairments. The proposed weighted-RWA (W-RWA) scheme captures the instantaneous state of the network by assigning weight values according to affecting impairments. The algorithm tries to minimize the effects of XPM and leave more feasible wavelengths for future requests, while avoiding damaging already established lightpaths. Since the weight assignment process can be made off-line, the W-RWA makes use of idle time before any request comes. The proposed Fixed Wavelength-Interval Allocation (FWIA) approach considers PLIs implicitly. This approach exploits the advantage of placing different modulation formats into separate channels which have adjacency with other modulation formats only at the boundaries of intervals.

3.2 Related Works

Various studies have been reported on the design of MLR networks considering static traffic. The authors in [21] deal with the design of MLR networks. A novel node architecture, where transparent *Etherpaths* (i.e., Ethernet tunnels on lightpaths) are established between these nodes, is proposed. The work in [22] shows that MLR networks are more cost-effective than SLR networks, and presents design methods for MLR networks. In [23], the authors aim to reduce the network cost in MLR networks using multiple modulation formats. They consider the tradeoff between susceptibility of higher line rates to impairments and the volume discount[1] of these line rates. In [24], the authors study protection in MLR networks. They propose cost effective transparent virtual topology design schemes for MLR networks which provides dedicated protection. In [25], the authors investigate the planning of 10/40 Gbps MLR networks, considering nonlinear interferences between 10 and 40 Gbps channels. The authors also present a set of tests to observe the trends in MLR planning for different network sizes. In [26], the authors present RWA algorithms to adapt the transmission reach of a connection, according to the modulation formats/line rates in the network. The algorithms allow planning the network so as to alleviate cross-rate interference effects. In [27], the authors present different path computation element (PCE) architectures, and experimentally evaluate these architectural solutions. The architectures perform RWA with either combined or separate impairment estimation, with on-line and off-line computation of impairment validated paths, and with the

[1]The discount given to a customer who buys a large quantity of goods.

possible utilization of a novel PCE Protocol (PCEP) extension. Traffic engineering performance, path computation delivery time, and amount of exchanged PCEP messages are used as the performance metrics to evaluate the architectures. In [28], design algorithms for MLR translucent networks considering energy efficiency are proposed. In [29], design and planning of translucent MLR networks are presented, considering multiple modulation formats with different reaches. In [30], tha authors investigate the effects of channel spacing and launch optical power for static traffic case. In [31], a differentiated quality of protection scheme is evaluated in terms of energy efficiency for MLR and orthogonal frequency-division multiplexing (OFDM) based networks. The authors study the problem of regenerator site selection and regenerator placement for mixed line rate translucent optical networks in [32, 33].

In [34], simultaneous transmission of 111, 43 and 10.7 Gbps channels is studied. Results of field trials are used to demonstrate the feasibility of transmitting 100G, 40G, and 10G together with 50 GHz channel spacing. Polarization-multiplexed, return-to-zero, differential quadrature phase-shift keying (POLMUX-RZ-DQPSK) is used to transmit 111 Gbps in parallel with 43 Gbps DPSK and 10.7 intensity modulated channels. The authors conclude that a 111 Gbps channel, neighboring with 43 and/or 10.7 Gbps channels, can be transmitted over long fiber links (>1000 km), with a careful choice of launch power (about 2 dBm). They also present the results of PMD effect on transmission with different network configurations. They conclude that the 111 Gbps channel is able to sustain 23 ps mean differential group delay with the help of digital processing in coherent detection. In [5], the authors present the impact of XPM impairments on simultaneous transmission of 111-Gbps POLMUX-RZ-DQPSK with 10.7 and 43 Gbps channels at 50 GHz channel spacing on field deployed fiber, with different launch powers. They find that the high data rates are more susceptible to launch power of neighboring channels than low data rates, in terms of XPM impairment. In [35], it is shown that coherent reception combined with digital signal processing can significantly increase the 100 Gbps system's tolerance against linear impairment effects, including polarization-mode dispersion and chromatic dispersion. In [36], it is shown that 16.4 Tbps capacity is possible with coherent detection, over a distance of 2500 km.

While various studies exist on the design of MLR networks with static traffic, there are only a few studies on the impairment-aware dynamic lightpath provisioning problem in MLR networks. In dynamic traffic case, lightpaths are established on demand, and stay in the system for their holding time. On the other hand, in static traffic case, a predetermined set of connections is given as input to the design phase that optimizes a defined objective. The authors in [37] consider the dynamic RWA problem in MLR networks without considering the impairments. The impairments are handled in [38] with the assumption of dynamic launch power capability, and a launch power control algorithm is proposed to improve the performance in terms of blocking probability. A PCE architecture to implement impairment-aware RWA is presented in [39]. In [19, 20, 40], the authors investigate impairment-aware RWA in MLR networks based on PCE. They propose various schemes for dynamic RWA based on *worst-case* and *guard-band*. In the worst-case scenario, a phase modulated (DQPSK and DP-QPSK) lightpath has OOK lightpaths on both neighboring wavelengths. Among the various proposed schemes, the one (first-fit worst-case with guard band, FF-W-GB) which exploits the benefit of both approaches, obtains the best performance. In [41], a scheme for dynamic grooming and RWA in translucent MLR networks is proposed.

3.3 Problem Definition

In this thesis, we consider the lightpath provisioning problem for dynamic traffic in MLR optical WDM networks, subject to physical-layer impairments. The problem can be formally stated as follows:
Given:

- A dynamic connection request with a given rate,
- Physical topology,
- Number of wavelengths carried by each fiber,
- Current network state, and
- PLI parameters.

The goal is to determine:

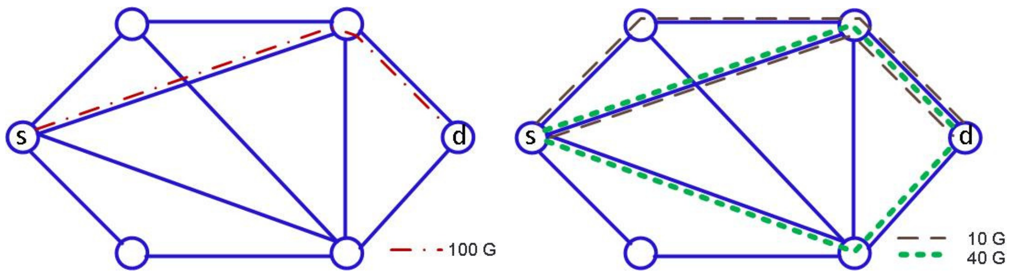
- Route over which the lightpath should be set up, and
- Wavelength to be assigned.

The objective of the problem is to maximize the number of established connections while satisfying the given BER for incoming connection, and to avoid disrupting the existing lightpaths. The problem is NP-hard, since it contains the NP-hard RWA problem [42] as a special case.

Proposed heuristic algorithms are given in the following two chapters.

4. INVERSE MULTIPLEXING BASED LIGHTPATH PROVISIONING ALGORITHMS

Inverse multiplexing (IM) is a technique that makes use of splitting higher line rate into smaller line rates, and transmitting signals at smaller line rates, where the high line rate is not possible due to PLIs. For high-line-rate requests (e.g., 40G, 100G), when the estimated BER of the selected path and wavelength exceeds the acceptable threshold, the request is split into sub-requests. These inversely-multiplexed requests can either be transmitted over the same wavelength on the same path, or they can be transmitted over a different wavelength on a different path. For example, if a 100G request (Figure 4.1 (a)) is not feasible on the shortest path, then the request would be split into 2×40G and 2×10G sub-requests (Figure 4.1 (b)), keeping the other properties of the connection request the same.



(a) Unfeasible 100G. (b) Inverse-multiplexed 100G request (2×40G, 2×10G).

Figure 4.1: Inverse multiplexing.

The network layer applications (e.g., [43]) enable to inversely multiplex the connection requests with high line rates into smaller line rates at the source node, propagate them separately over a transparent MLR network, and then combine them back at the destination node.

As a part of this thesis, we investigate the IM gain in MLR networks for the impairment-aware dynamic lightpath provisioning problem. The details and the results of this study are presented in Appendix C. The results of the study indicate that the approaches employing IM can improve lightpath provisioning performance. In this

Table 4.1: Proposed algorithms using IM.

	BB	**MSD**
Shortest path	SP-BB	SP-MSD
Minimum hop	MH-BB	MH-MSD
Least congested path	LCP-BB	LCP-MSD

thesis, we propose various IM-based schemes to account for the impairment-aware dynamic lightpath provisioning problem in MLR optical networks. The performances of the proposed schemes are evaluated through simulations for different network topologies.

4.1 Algorithms

In this thesis, we propose various schemes based on IM to account for lightpath provisioning in MLR optical transparent networks. Three path selection algorithms are used to compute a path for a connection request from source s to destination d: shortest path (SP), minimum hop (MH) path, and least congested path (LCP). Two wavelength-assignment schemes are employed with each path-selection algorithms: Best-BER (BB) and maximum spectral distance (MSD). Overall, the proposed schemes are summarized in Table 4.1.

4.1.1 Path selection schemes

The proposed schemes use three different path-selection algorithms: SP, MH, and LCP. SP ensures the shortest distance from s to d, while MH minimizes the number of nodes on the selected path to minimize linear XT effect. The LCP method is a modified version of the LCP algorithm introduced in [44]. The algorithm used in this thesis selects the appropriate path among k-shortest paths [45]. The algorithm first finds k-shortest paths, and then selects the path that has the maximum number of available wavelengths. Note that in a transparent WDM network, wavelength conversion at intermediate nodes is not allowed. LCP aims to minimize the effects of linear and non-linear XT.

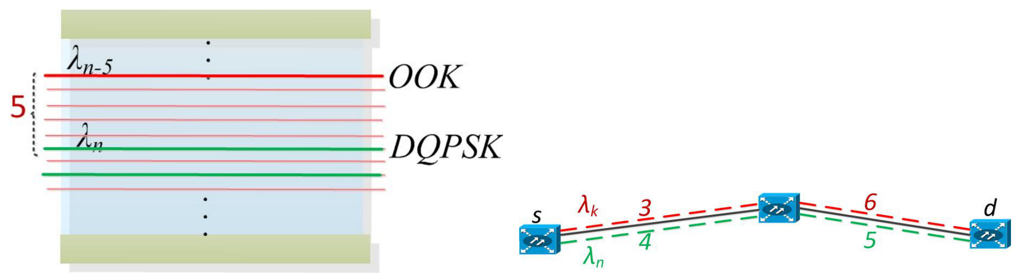
4.1.2 Wavelength assignment schemes

Best-BER (BB): This scheme is a modified version of the BB algorithm introduced in [46, 47]. It aims to assign the wavelength having the minimum BER on the selected path. All available wavelengths on the selected path are sorted in ascending order according to their BER value. If BER of the selected wavelength is above a threshold, the wavelength is selected.

Maximum Spectral Distance (MSD): This scheme selects the appropriate wavelength that has the MSD on the selected path. Spectral distance is the distance between xPSK and the closest OOK channels, on the same path. For xPSK signals, MSD of a wavelength w on a path from s to d is computed as:

$$Max_{s,d}(Min(\delta\lambda_{(i,j)}^{w,w'})) \quad \textbf{(4.1)}$$

where $\delta\lambda_{(i,j)}^{w,w'}$ is the number of wavelengths between wavelengths w (xPSK channel) and w' (OOK channel) on link *(i,j)*. MSD computation is depicted in Figure 4.2.



(a) Spectral distance on a link. (b) Spectral distances on a path.

Figure 4.2: Maximum spectral distance calculation.

In Figure 4.2 (a), spectral distance of the projected link is 5, where, λ_n and λ_{n-5} are occupied with different line rates. The minimum of these values along the path gives the spectral distance of the path. The path having largest spectral distance is selected by MSD. Given the wavelengths, and the existing lightpaths in Figure 4.2 (b), MSD_{λ_n} is 4 (that is: for the given wavelength λ_n, along the path from s to d, spectral distance between xPSK and OOK channels is 4), and MSD_{λ_k} is 3. The wavelength λ_n, with spectral distance of 4, is selected by MSD.

In MSD wavelength assignment scheme, all the available wavelengths on the selected path are sorted in descending order according to their MSD value. This wavelength assignment scheme aims to minimize the XPM effect of OOK signals on xPSK signals. MSD differs from the wavelength selection approach given at [48] in that MSD dynamically looks for the wavelength that is most separate than the occupied wavelengths.

A generic algorithm that employs IM is used to evaluate the performance of proposed schemes (see Algorithm 1). If the BER value for the requested line rate is not

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Algorithm 1 Generic algorithm to implement proposed schemes with IM.

I- Find appropriate path and wavelength (candidate lightpath) using one of the proposed schemes.

- If a path with an available wavelength does not exist, reject the request.

II- Compute BER value for the candidate lightpath with requested line rate.

III- Check if BER of the candidate lightpath is below acceptable BER threshold.

- If the estimated BER is above the threshold, then inversely multiplex the request into sub-requests.
- Take these sub-requests as new requests and run the algorithm for each.
- If any of sub-requests cannot be established, then reject the whole request.

IV- Verify existing lightpaths with candidate lightpath(s).

- If any of them becomes infeasible, reject the request.

V- Set up the lightpath(s).

VI- Release the connection(s) after holding time.

---

acceptable on the selected wavelength, then IM is applied to the request. If a sub-request is not feasible, then IM is applied to the sub-request, as well. If the line rate of the rejected request is minimum (i.e., 10G), then no IM is considered. In case any sub-request is rejected, the whole request is rejected.

After finding the candidate route and wavelength with acceptable BER, existing lightpaths are also verified. If any existing lightpath is weakened to have BER value more than acceptable threshold, then the candidate lightpath is not allowed to be established.

4.2 Illustrative Numerical Examples

In this study, we consider an optical WDM network in which each node can support transmission at 10, 40, and 100G line rates. NSFNET, EON and a simple topology with 6 nodes (see Appendix B) are used to evaluate the performance of the proposed schemes. EON has shorter link distances (average ≈550 km) than NSFNET (average ≈930 km), and the 6-node topology has same average link distance with NSFNET. Each node has limited number of transponders and receivers for each line rate.

Physical links have inline (EDFA) amplifiers every 82 km, with 70 km standard single mode fiber, and 12 km dispersion compensation fiber. Fixed grid with 100 GHz channel spacing and carrying 40 wavelengths is employed, and wavelength continuity constraint is applied for intermediate nodes. For LCP-based algorithms, we used k=3 to find *k*-shortest paths. Connection requests arrive according to Poisson distribution with exponentially-distributed holding times. Requests for different line rates are dynamically generated according to uniform distribution. For each line rate, transceiver numbers are given in advance and the algorithms are not allowed to exceed these numbers. We ran the simulations for one million connection requests. For different random number generator seeds, we obtained consistant results. Other system parameters are given in Appendix A.

An incoming request can be rejected due to non-sufficient network resources (*resource blocking*) or affecting impairments (*physical-layer blocking*) [1]. We evaluated the physical-layer blocking and resource blocking performances of the algorithms separately to see the effects of IM. We also implemented the same impairment-aware provisioning schemes without IM, using the same parameters, to see how the performance is changed with IM. Among impairment-aware provisioning schemes without IM, Shortest-Path Best-BER (SP-BB-noIM) shows the best performance in terms of blocking; thus we show the results of SP-BB-noIM as a baseline in the figures for comparison with the schemes using IM.

Figure 4.3 shows the blocking ratio due to PLIs for NSFNET topology. The traffic load is given in Erlangs. PLIs induced by established lightpaths increase in parallel with increasing traffic load; thus, the blocking ratio increases for all algorithms. The SP-MSD shows the best blocking probability performance for all traffic loads. The LCP-MSD shows good blocking probability performance for lower traffic loads, but it experiences a performance decrease with increasing traffic load. This performance decrease has two reasons: the algorithm hardly finds a distant wavelength along the path, and average length of selected paths increases while selecting the path

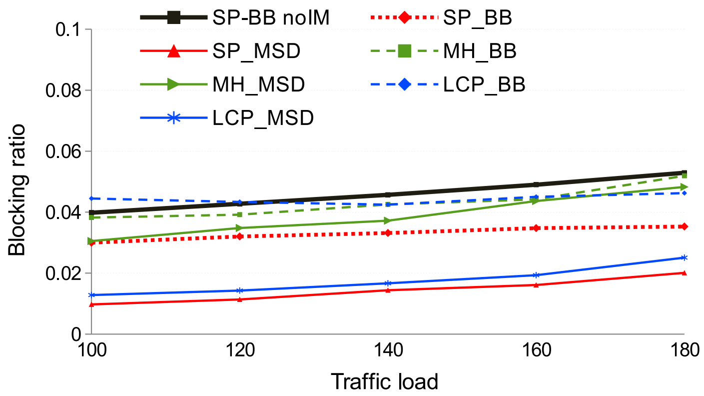


Figure 4.3: Blocking ratio due to PLIs (NSFNET topology).

that has more available wavelengths. Although it becomes difficult to find distant wavelengths between xPSK and OOK signals for high traffic loads, MSD experiences better performance than BB for all routing schemes. The SP-based algorithms experience regular decrease in performance while the traffic load increases. Although the MH-based schemes using IM show better performance than not using IM, their performances are below the SP and LCP-based schemes. The difference between SP-BB-noIM and SP-BB shows that using IM yields a good performance increase in terms of blocking probability due to PLIs.

Figure 4.4 shows the blocking ratio due to PLIs for EON topology. The EON topology

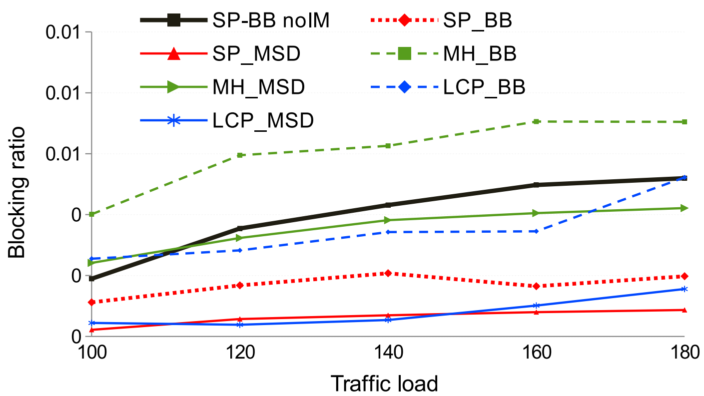


Figure 4.4: Blocking ratio due to PLIs (EON topology).

has shorter link distances than NSFNET, so the blocking ratio due to PLIs for this topology is less than NSFNET. On the other hand, increasing average hop-count of paths increases linear XT in this topology. Increasing average hop-count also increases the wavelength-link usage, so resource blocking becomes higher for medium and high traffic loads (see also Figure 4.6) and blocking ratio due to PLIs becomes lower.

SP-MSD shows the best blocking performance in this topology for all traffic loads. LCP-MSD shows good performance for low traffic, but it experiences performance decrease with traffic-load increase.

Figure 4.5 shows the blocking ratio due to PLIs for the 6-node topology. Although this topology has longer link distances than EON topology, it has less blocking ratio than EON due to increased connectivity. The other reasons for better blocking ratio performance are: less average hop-count and lower average lightpath length. In this topology, LCP-MSD shows better performance than the other schemes in terms of PLI blocking for low and medium traffic loads. For high traffic loads, since

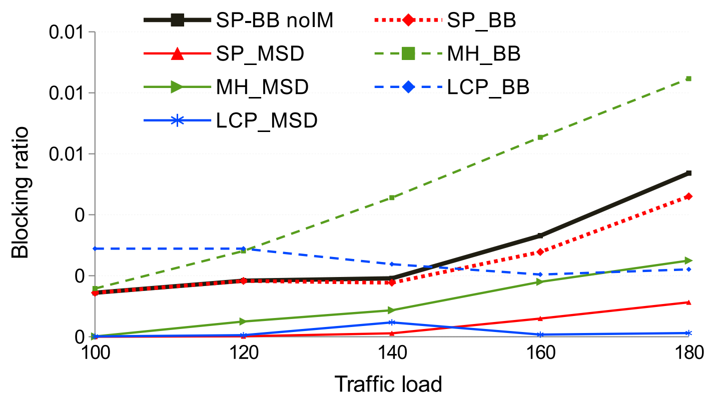
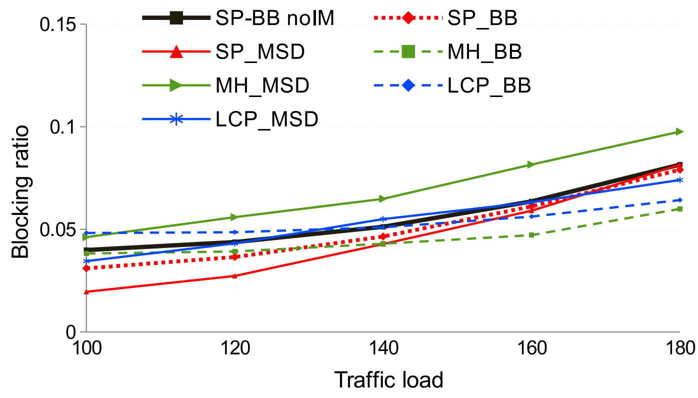


Figure 4.5: Blocking ratio due to PLIs (6-node topology).

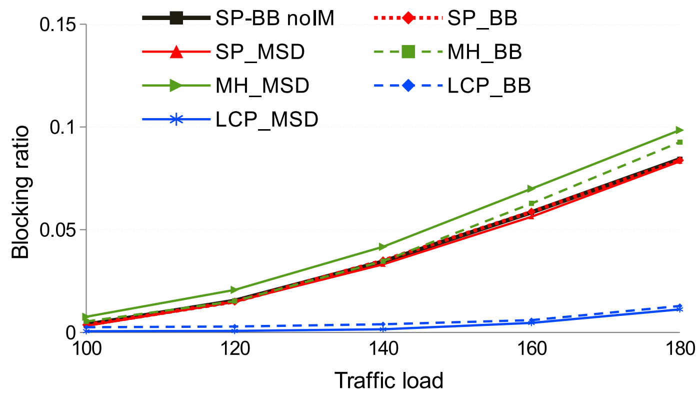
the resource blocking increases, the performance difference between IM-employing and not employing schemes diminishes. Figure 4.6 shows the total (physical-layer and resource) blocking ratio for both IM-employing and not employing schemes for different topologies.

The algorithms having the same path-selection scheme show similar total blocking performance for all topologies. Although the LCP-based algorithms do not have best performance in terms of PLI blocking for high traffic loads, LCP-BB and LCP-MSD have best performance for total blocking performance for all traffic loads. Total blocking performances of the algorithms show that signal quality is highly dependent on the state of the network. Thus, LCP-based algorithms, where the path having maximum number of available wavelength is selected among *k*-shortest paths, show the best blocking ratio performance.

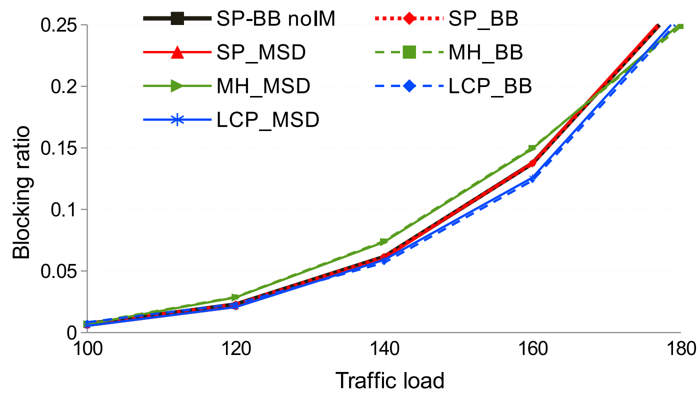
The results for SP-BB-noIM and SP-BB algorithms show that blocking ratios decrease with IM for low traffic loads, but their performances come closer with increasing traffic



(a) NSFNET.



(b) EON topology.



(c) 6-node topology.

Figure 4.6: Total (physical-layer and resource) blocking ratio results of proposed schemes for different topologies.

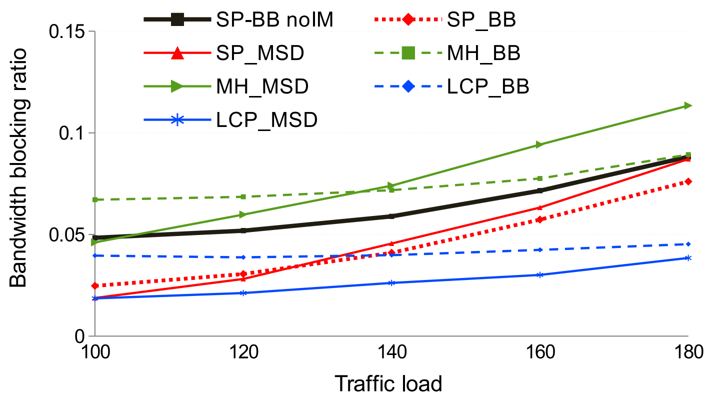
load. IM increases the performance of blocking due to PLIs, but resource blocking becomes the dominant factor determining the total blocking performance for high traffic loads.

Pure blocking probability considers all requests as the same, but blocking a request with 100G causes 10 times more throughput loss than a 10G request. Bandwidth blocking ratio (BBR) is defined as the amount of bandwidth blocked over the amount of bandwidth offered [49]. We also evaluated the BBR performance of inverse multiplexing scheme. Figure 4.7 shows the total BBR performances of proposed schemes.

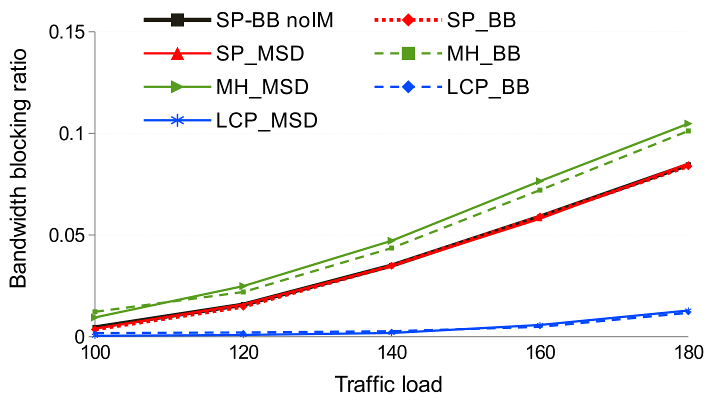
The algorithms show similar performance with total blocking ratio performance for all topologies. The results for NSFNET topology indicate that MSD-based approaches have better results for lower traffic, where distant wavelengths for different modulation formats are selected. For higher traffic loads, the performance of BB-based approaches have less blocking ratio, because MSD-based approaches fail to find distant wavelengths. LCP-based algorithms show better BBR performance than other schemes.

The SP-based scheme employing IM (SP-BB) shows better performance than SP-BB-noIM up to a level, where it hardly finds network resources for inversely multiplexed requests. After that, IM does not help to increase the achieved throughput because IM uses more wavelengths to accommodate the requests, and the BBR due to insufficient resources increases.

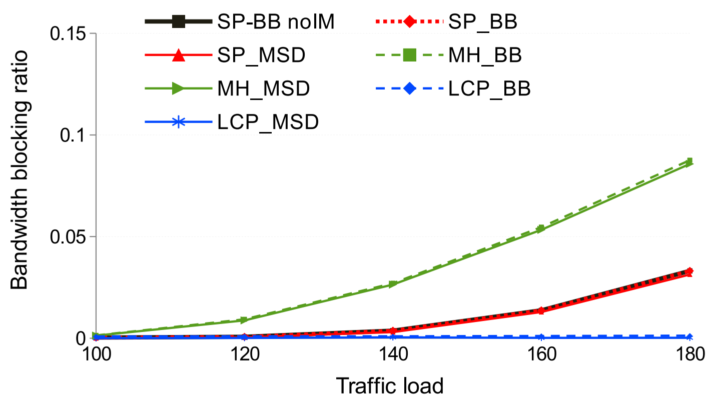
The main drawback of IM is the additional network resource consumption, in terms of wavelength-links. Figure 4.8 gives the additional network resource usage ratio ($\frac{Wavelength-link_{IM}}{Wavelength-link_{Total}}$) for NSFNET. The numerator of the fraction is the wavelength-links of established lightpaths using IM, representing the total amount of wavelength-links which are occupied due to infeasible high line rates. The denominator of the fraction is the total wavelength-links of established lightpaths. For example, instead of an infeasible 100G lightpath with 3 wavelength-links from s to d, an algorithm using IM establishes $2\times$40G and $2\times$10G lightpaths on the same path. Thus, the algorithm with IM consumes 9 additional wavelength-links for the same request. For low traffic loads, IM leads to high additional network resource consumption, because the network has free wavelengths to be assigned for inversely-multiplexed requests. The IM schemes occupy more wavelength-links up to 1/3 of total wavelength-links of lightpaths. LCP-MSD experiences the highest additional wavelength-links consumption for all traffic loads. Together with total blocking performance (see Figure 4.6), it can be



(a) NSFNET.



(b) EON topology.



(c) 6-node topology.

Figure 4.7: Bandwidth blocking ratio results of proposed schemes for different topologies.

said that LCP-MSD increases the blocking performance with a cost of additional network resource usage. Additional wavelength-links usage of MH-MSD is high for low traffic loads, but it decreases with increasing traffic. SP-BB causes less additional wavelength-links usage for all traffic loads. For high traffic loads, the additional

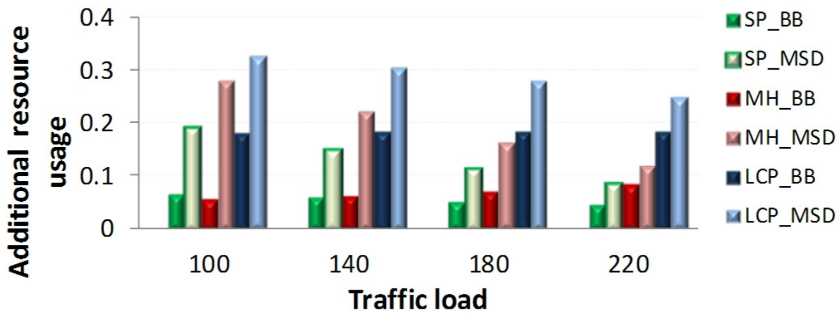


Figure 4.8: Additional network resource (wavelength-links) usage of the proposed schemes for NSFNET.

network resource consumption ratio of IM-based schemes decrease due to insufficient resources.

Figure 4.9 gives the additional network resource usage ratio of the approaches at a certain level of blocking probability. The approaches using MSD wavelength selection

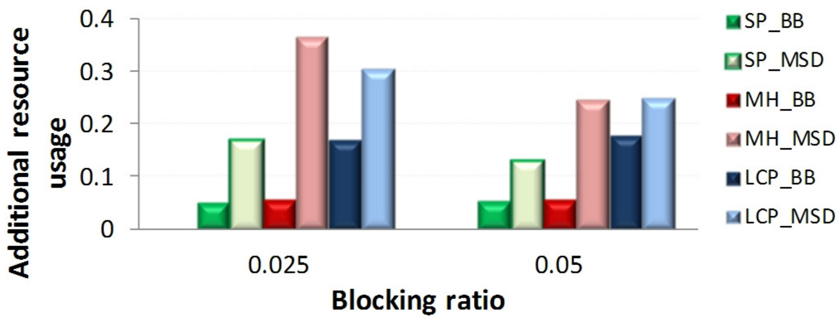


Figure 4.9: Additional resource usage at certain blocking ratio.

scheme use more additional wavelength-links than BB-based approaches to achieve the given blocking ratio. Since MH selects the path that uses minimum wavelength-link, any performance increase using IM leads to more wavelength-link usage.

4.3 Conclusion

In this chapter, we presented the performance of inverse multiplexing based lightpath provisioning schemes in MLR networks. IM is employed where high line rates are infeasible due to PLIs. Employing IM causes gain in terms of blocking probability due to PLIs, but after reaching a level where network resources do not let the algorithm to find an available path and wavelength, blocking probability performance of IM gets closer to the scheme that does not employ IM [50].

We proposed various approaches (SP-BB, SP-MSD, MH-BB, MH-MSD, LCP-BB, and LCP-MSD) employing IM for the problem. The proposed schemes use SP, MH, and LCP algorithms to find the appropriate path. Wavelength assignment is done according to BB or MSD approaches. Within these algorithms, IM is employed where high line rates are not feasible due to PLIs.

Our algorithms are evaluated through simulations. The results indicate that the performances of the algorithms differ according to topologies and traffic load. But in all cases, algorithms employing IM outperform the algorithms that are not employing IM in terms of blocking ratio.

The performance increase obtained from IM comes with a trade-off. The algorithms employing IM use more wavelength-links to accommodate the same amount of request. LCP-based algorithms employing IM experience the worst performance in terms of additional wavelength-links usage. To improve the performance in terms of blocking ratio, network operators can use adaptive schemes, which consider the resources they have and the state of the network.

5. DYNAMIC LIGHTPATH PROVISIONING ALGORITHMS

In this chapter, we propose two novel approaches to handle PLIs in lightpath provisioning for MLR networks. The first approach takes PLIs into account implicitly. It partitions the wavelengths into groups, assigns these groups to line rates, and establishes lightpaths with different modulation formats over the assigned wavelength groups. The second approach handles the problem with a novel weight assignment scheme that accounts for PLIs. The details of the proposed algorithms are explained in the following sections.

5.1 Fixed Wavelength-Interval Allocation (FWIA)

Linear and non-linear noise accumulated along the path degrades the optical signal quality. This noise depends on various system parameters (e.g., symbol rate, number of channels, channel spacing, fiber type). Interchannel nonlinearities are particularly important to advanced modulation formats at high (40G/100G) bit rates. Although every optical channel induces interchannel nonlinearity on neighboring channels, adjacency of OOK channels has more detrimental effects on advanced modulation formats. To prevent, especially, OOK channels to negatively affect high bit rate channels, FWIA partitions wavelengths into groups, where each group is assigned to a different modulation format. This kind of wavelength allocation considers PLIs implicitly, and avoids assigning adjacent channels to different modulation formats.

The number of wavelength groups is equal to the number of different line rates (see Figure 5.1). The proposed algorithm is given in Algorithm 2.

The algorithm first finds the shortest path, and then looks for an appropriate wavelength. For an incoming request, from source (s) to destination (d), a wavelength is selected from the group allocated for the requested line rate. The algorithm starts searching for an appropriate wavelength from the center wavelength of the allocated group of wavelengths. It aims to find the one that is less exposed to XPM, and to leave more feasible-wavelengths for future requests. The search goes towards the

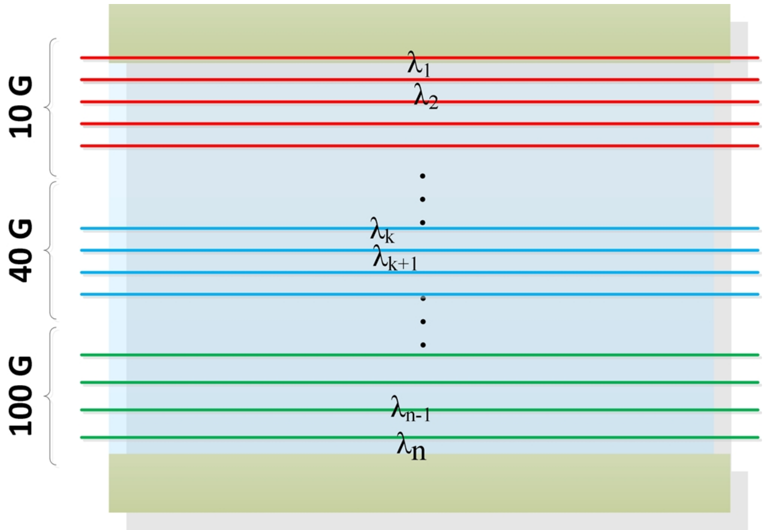


Figure 5.1: Fixed Wavelength-Interval Allocation.

Algorithm 2 Fixed Wavelength-Interval Allocation (FWIA) Scheme.

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1. Partition the total wavelengths into intervals.
2. Get the request.
3. Find shortest path from *s* to *d* with an available wavelength,
   - If a path with an available wavelength does not exist, reject the request.
   - Else find an appropriate wavelength:
     - Start from the center wavelength of the interval.
     - Search towards the sides of the interval.
4. Validate the path for minimum BER requirements (candidate).
5. Verify existing lightpaths:
   - If any of the existing lightpaths' BER becomes unacceptable,
     - Look for another wavelength (multiple-attempt).
     - Reject the request (single-attempt).
6. Set up the lightpath.
7. Tear down the lightpath after holding time.

---

sides. First, one half of the interval which does not cause (or expose) to XPM effect is searched. If there is not an available wavelength in this half of the interval, the algorithm searches the other half of the interval, again beginning from the center. After finding an available wavelength, BER is estimated for this path-wavelength, considering the current state of the network. If the estimated BER is acceptable, then this path-wavelength pair is called the candidate lightpath. After finding a candidate lightpath, existing lightpaths are examined. If any of the existing lightpaths is damaged by this candidate lightpath, the algorithm searches for another wavelength. This is called *multiple-attempt* scenario. In *single-attempt* scenario, if the candidate lightpath damages any existing lightpath, the request is rejected without looking for another wavelength.

5.2 Weighted Routing and Wavelength Assignment (W-RWA)

In this approach, we use an auxiliary graph $G(V,E)$ to keep track of impairments. This auxiliary graph is constructed by replicating the network's original graph $G_0(V_0,E_0)$ for each line rate. The auxiliary graph is used to assign weight values to the wavelengths to account for the impairments in MLR networks.

5.2.1 Auxiliary graph construction

To construct the auxiliary graph $G(V,E)$, we first replicate the physical nodes (V_0) as the number of line rates. The i^{th} vertex of the auxiliary graph (Fig. 5.2(a)) is denoted by $\{V_0^i, V_1^i, ..., V_k^i, ..., V_R^i\}$, where R is the number of line rates.

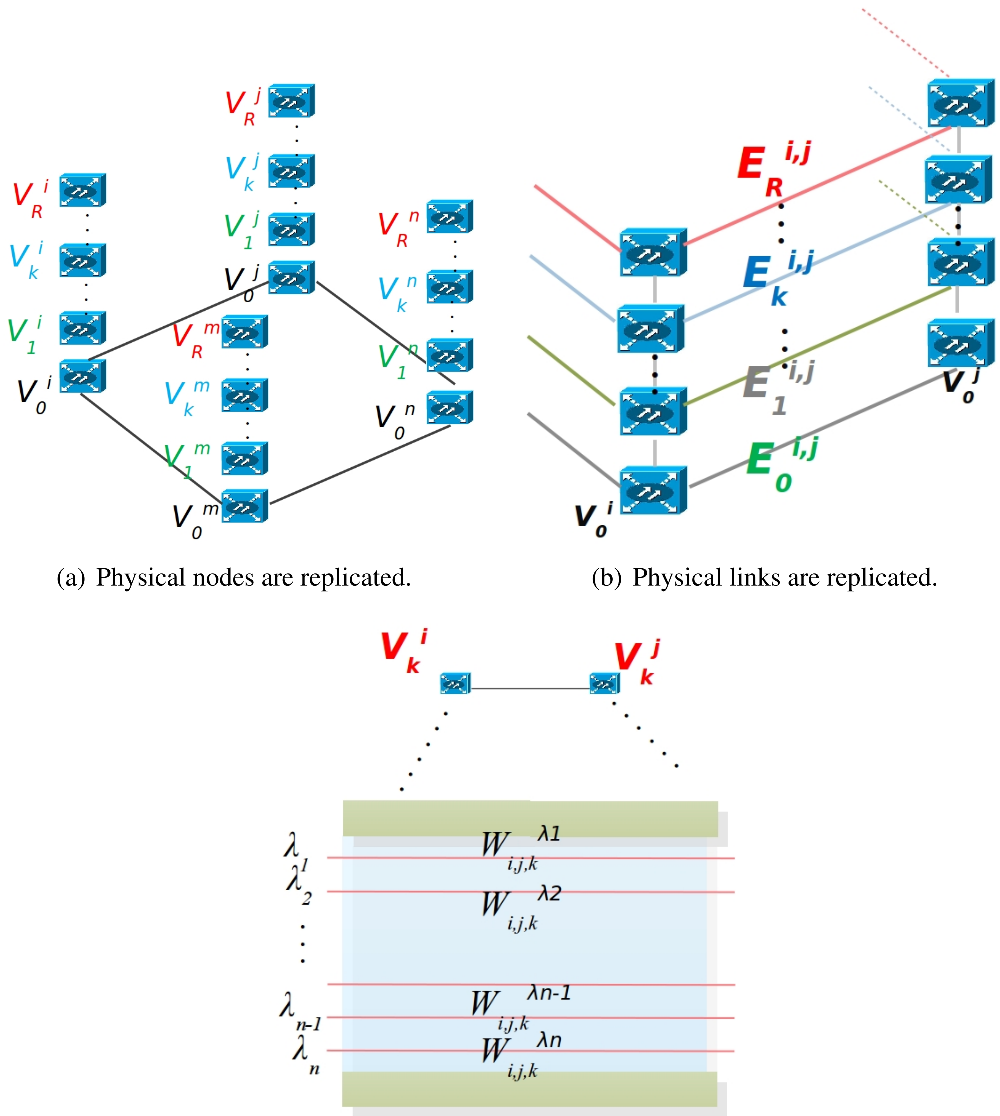
Then, the physical links ($E_0^{i,j}$) connecting nodes (V_0^i,V_0^j) are replicated. The links of the new graph (Fig. 5.2(b)) are denoted by $\{E_0^{i,j}, E_1^{i,j}, ..., E_k^{i,j}, ..., E_R^{i,j}\}$.

Each wavelength on a link is considered separately and associated with a weight value ($W_{i,j,k}^{\lambda}$), which is assigned according to the current state of the network (Fig. 5.2(c)). This weight value represents the propagation penalty of transmitting the signal over a specific wavelength (λ) on that physical link (i, j) with specific line rate (k).

The weight values are initialized before any connection request comes, according to linear impairments (ASE, losses, CD, and PMD). After each lightpath is established or released, the weight values are recalculated along the path (s to d) for the wavelengths within the guard band (GB) of the newly established lightpath. The weight values are calculated as discussed in the following section.

5.2.2 Weight assignment

We propose a novel weight assignment scheme to capture the PLIs. The weight values represent linear and non-linear impairments that occur on the physical links (ASE,



(a) Physical nodes are replicated.

(b) Physical links are replicated.

(c) Each wavelength on a link associated with a weight value.

Figure 5.2: Auxiliary graph construction.

losses, CD, and SPM), and on the nodes (XT and losses). Unlike OOK modulated channels, DQPSK and DP-QPSK channels are also affected by the intensity variations of neighboring channels. XPM effect of OOK signals on DQPSK and DP-QPSK channels is neglected after GB. Weight assignment for impairments induced at nodes and links are evaluated as described below.

Weight assignment for a vertex: The weight of a node represents the propagation penalty due to crosstalk within that node. Two different types of switch crosstalks (inter and intra-band crosstalk, see Section 2.3) are considered in this study.

Each vertex j of the auxiliary graph is assigned a weight value ($W^{\lambda}_{V^j_k}$) for each wavelength of the input/output port, where k is the requested line rate. Let N be the number of ports (input/output) of each node, then crosstalk values at node V^j_k on wavelength λ are taken into account as vertex weight value ($W^{\lambda}_{V^j_k}$) as follows:

$$W^{\lambda}_{V^j_k} = \omega^{\lambda}_{XT_a}.v^{j,\lambda\mp1}_{XT_a} + \sum_{p=1}^{N} \omega^{\lambda}_{XT_b}.v^{j,\lambda,p}_{XT_b} + \kappa \tag{5.1}$$

where $\omega^{\lambda}_{XT_a}$ and $\omega^{\lambda}_{XT_b}$ indicate the predefined weight factors of the crosstalk components; $v^{j,\lambda\mp1}_{XT_a}$ and $v^{j,\lambda,p}_{XT_b}$ are the binary variables indicating the presence of a lightpath causing crosstalk on port p of node j on wavelength λ; and κ is the adjusting weight value indicating the losses caused by the taps, demultiplexers, switching elements, and multiplexers inside the node.

The weight caused by node j is accounted with the link i,j for specific wavelength λ. The parameters used in node weight evaluation model are given in Appendix A.

Weight assignment for a link: Each wavelength (λ) on the edge ($E^{i,j}_k$) of the graph ($G(V,E)$) is assigned a weight value $W^{\lambda}_{i,j,k}$. The initial weight values are calculated considering ASE and SPM using Equation (5.2). The weight value of the affected wavelengths of the links along the path are recalculated each time a lightpath is established or released.

Each link weight value encompasses various impairments, and dynamically changes according to XT and XPM. The XT effect of the established lightpath is evaluated using Equation (5.1). The wavelengths (λ_d) within guard band (+/-GB) are added a weight value for XPM effect, depending on their distances ($|\lambda_n - \lambda_d|$) to the lightpath established on λ_n. The XPM effect decreases with the ratio of $\frac{1}{(\Delta\lambda)^2}$ [19], where $\Delta\lambda$ gives the number of wavelengths between affecting signal and the actual signal. Specifically, we define the weight-assignment scheme for a wavelength (λ_d) at bit rate k on a link ($E^{i,j}_k$) as follows:

$$\begin{aligned} W^{\lambda_d}_{i,j,k} &= W^{\lambda_d}_{V^j_k} + m.\omega^{\lambda}_{ASE} + \omega^{\lambda}_{SPM} + \\ &\sum_{k=1}^{R} \sum_{g=\lambda_n-GB}^{\lambda_n+GB} \frac{1}{(\Delta\lambda)^2} \omega^{k}_{XPM} \cdot v^{i,j,k}_{g} + \zeta \end{aligned} \tag{5.2}$$

where m is the number of spans within the link, R is the number of line rates, ω^{λ}_{ASE}, ω^{λ}_{SPM}, and ω^{k}_{XPM} are the predefined weight factors of ASE, SPM, and XPM, respectively. These values are assigned considering their effects on BER. These factors can be static or they can be changed in time. $\nu_g^{i,j,k}$ denotes the existence of affecting lightpaths on link i, j with rate k on wavelength g, and ζ stands for the adjusting weight value for other impairments. Together with κ value in Equation (5.1), ζ is used to help the algorithm to select the lower hop-count path when more than one path have same total weight value. The parameters used in link weight evaluation model are given in Appendix A.

Same modulation promotion: Another feature of the weight assignment scheme is the *same modulation promotion*, which gives promotion points (Ξ) to adjacent channels that use the same line rate (k) as the already established lightpaths. After each lightpath is established, a *promotion* value is subtracted from weight of the wavelengths (λ_d) within GB, according to their distances ($|\lambda_n - \lambda_d|$) to the established lightpath over λ_n. This promotion value is relatively small compared to the weight values of impairments. The weight value of a wavelength (λ_d) at a specific bit rate R_r on a link (i, j) is promoted as:

$$W_{i,j,k}^{\lambda_d} = W_{i,j,k}^{\lambda_d} + (-1)e^{(-1)|\lambda_n - \lambda_d|} \cdot \Xi \tag{5.3}$$

With this promotion, the same modulation format is encouraged to be selected for adjacent channels; therefore, the lightpaths using the same modulation format tend to be closely located. The algorithm improves the awareness of the current state of the network, minimizes the effects of XPM, and avoids degrading the signal quality of already established lightpaths.

Weights, increased due to lightpath establishment, are decreased when the lightpath is torn down (inverse update).

5.2.3 Algorithm

The W-RWA algorithm is given in Algorithm 3.

When a request comes, the algorithm looks for the minimum-weighted path over the auxiliary graph. The algorithm guarantees the signal quality along the lightpath by avoiding higher weighted paths. If a path cannot be found, then the request is rejected (resource blocking). It is also possible to find more than one path with same

Algorithm 3 Impairment-Aware Weighted-RWA (W-RWA) Scheme.

1. Initialize the Auxiliary Graph.
2. Get the request.
3. Find minimum-weighted path(s).
   - If no available path exists:
     - Reject the request.
   - If more than one path available with same weight value.
     - Choose the path with minimum estimated BER.
       - If more than one have same estimated BER.
         - Choose the candidate with maximum spectral distance to other modulation formats.
   - Validate the path for minimum BER requirements.
   - Verify existing lightpaths.
     - If any of existing lightpaths' BER becomes unacceptable:
       - Look for another minimum-weighted path (multiple-attempt)
4. Set up the lightpath.
5. Update the Auxiliary Graph.
   - Add weight to adjacent wavelengths for other modulation formats.
   - Add promotion points to neighboring wavelengths for the same modulation format.
6. Tear down the lightpath after holding time.
7. Update (Inverse) the Auxiliary Graph.

---

minimum-total-weight value. In this case, estimated BER values of these paths are evaluated, and the path with minimum BER is selected.

For low traffic loads, it is possible to obtain same estimated BER values for different wavelengths on the same route. In this case, the wavelength that has the *maximum spectral distance* is selected (see Section 4).

After finding the appropriate path and the wavelength, the quality of signal is validated using the BER evaluation models given in Section 2.3. The selected path and the wavelength is called a *candidate*, if the estimated BER value is acceptable. Otherwise, the request is rejected (physical-layer blocking). Before establishing the lightpath over this candidate path and wavelength, the signal quality of existing lightpaths (only the ones which are expected to be affected from the new lightpath) are also verified.

Promotion points are added to neighboring wavelengths for the same modulation formats.

Let V be number of vertices, and E number of edges, then the worst case complexity of the W-RWA algorithm is $O(w \times (|V|logV + |E|) + O_{BER})$, where O_{BER} is the computational cost of BER calculation. Since all the wavelengths are associated with a weight value, the W-RWA algorithm runs the shortest path algorithm w times. The FWIA approach looks for the shortest path that has an available wavelength within the allocated wavelength-interval. Thus it runs the shortest path algorithm w/r times for worst case, where r is the number of line rates.

5.3 Illustrative Numerical Examples

In this thesis, an optical WDM network in which each node can support transmission at 10, 40, and 100G line rates is considered. NSFNET network topology (see Appendix B) is used to evaluate the performance of different schemes. Physical links have inline (EDFA) amplifiers at every 82 km, with 70 km standard single mode fiber, and 12 km dispersion compensation fiber. Fixed grid with 50 GHz spacing carrying 80 wavelengths is employed. Wavelength continuity constraint is applied for intermediate nodes. Connection requests arrive according to Poisson distribution with exponentially distributed holding time. Requests for different line rates are dynamically generated according to both uniform and skewed traffic. In uniform traffic, each incoming request may be 10, 40, or 100G with equal probability. Skewed traffic profile generates equal total amount of bandwidth request for each line rate. Other system parameters are given in Appendix A.

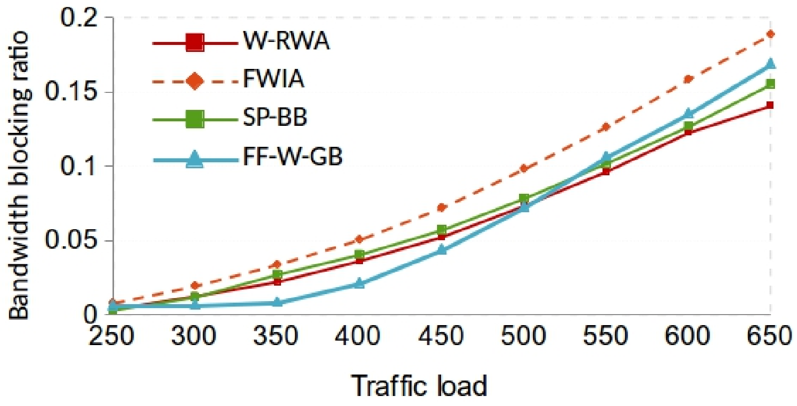
The quality of the signal is evaluated using the BER model in Section 2.3. In our model, phase modulated (40/100G) channels do not have XPM effect on each other and the predefined ASE, CD, and SPM weights are same for all wavelengths. In FWIA, the number of wavelengths to be allocated for each line rate can be determined by network operators according to statistical data on distribution of line rates of the requests. In this study, requests for line rates are randomly generated using uniform distribution, and wavelengths are equally partitioned among the line rates.

We compared our proposed approaches (W-RWA and FWIA) with the First-Fit with Worst-case scenario with GB (FF-W-GB) approach. In this approach, first XPM is considered in worst-case scenario. If the estimated BER of the lightpath is acceptable in worst-case, GB is not considered to establish the lightpath. If the BER is acceptable only by neglecting XPM, neighboring wavelengths are reserved to be GB.

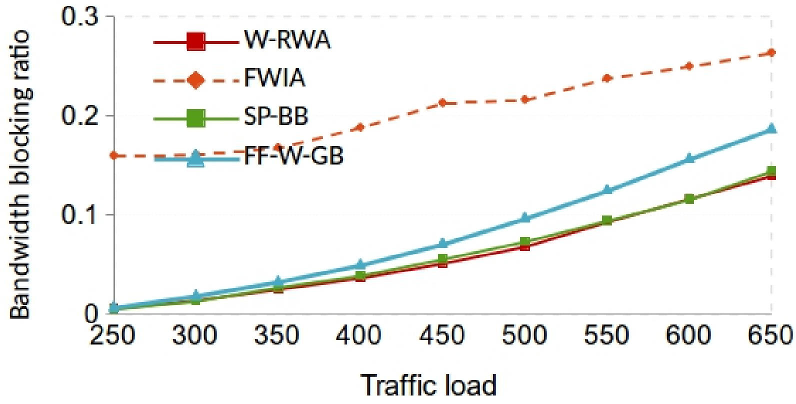
We also compared our approaches with the Shortest-Path with Best-BER (SP-BB) algorithm. In SP-BB, first the shortest path is found, and then, BER value is estimated for each wavelength on the shortest path, and finally the Best-BER (the one with the minimum BER value) channel is selected. The shortest-path algorithm is modified to find the shortest path with at least one available wavelength. This modification is made to have a fair comparison with the Weighted-RWA approach. W-RWA selects the minimum-weighted path, which is not necessarily the shortest path. If the estimated BER value is within the acceptable threshold, then the path and wavelength found is regarded as a candidate, otherwise, the request is rejected. After finding the candidate path and wavelength, existing lightpaths, which are expected to be affected by the candidate lightpath, are checked for signal quality.

Calculation of pure blocking probability treats all requests as the same, but blocking a request with 100G causes 10 times more throughput loss than a 10G request. Thus, blocking different requests with different line rates is not the same in terms of the achieved throughput. Figure 5.3 shows the bandwidth blocking ratio (BBR) for different lightpath provisioning schemes with uniformly distributed traffic.

In multiple-attempt scenario, FF-W-GB algorithm shows better performance than the other approaches for low link utilization levels. It exploits the benefit of putting guard band for higher line rates, but its performance degrades due to higher wavelength utilization for high traffic loads. To use multiple attempts, W-RWA picks the wavelengths having at most 1% more weight than the total weight of the minimum-weight path. For high utilization levels, W-RWA shows better performance, because W-RWA is rate aware and it aims to keep more feasible wavelengths for future requests. FWIA shows fair performance for the multiple-attempt scenario. Single-attempt scenario performances are similar to multiple-attempt scenario for all approaches except FWIA. This approach suffers from XT effect of same modulation



(a) Multiple attempt.



(b) Single attempt.

Figure 5.3: BBR of different schemes with (a) multiple-attempt and (b) single-attempt scenarios, for uniformly-distributed traffic.

channels. These results show that, in the multiple-attempt scenario, W-RWA takes the advantage of considering different physical paths having the same weight value.

We ran the simulations also for a skewed traffic profile. BBR for skewed traffic with multiple-attempt scenario is given in Figure 5.4. Line-rate-aware approaches, W-RWA

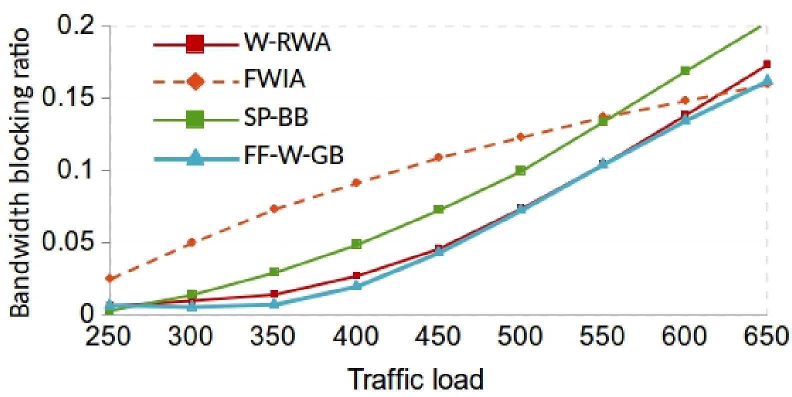
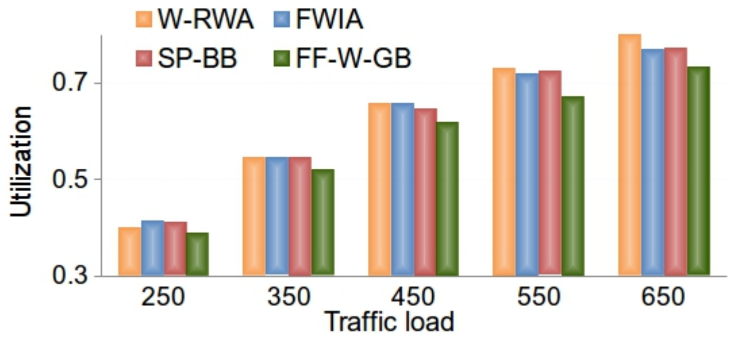


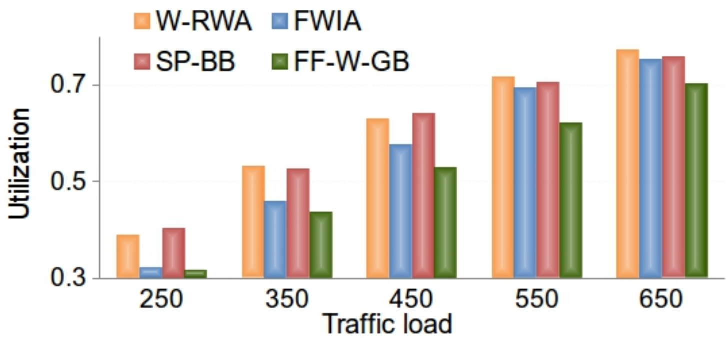
Figure 5.4: BBR of different schemes with multiple-attempt scenario, for skewed traffic.

and FF-W-GB, give better BBR performance than the others. Since FWIA allocates wavelengths for higher line rates, it shows better performance for very high traffic loads.

Figure 5.5 indicates the maximum utilization levels of the network with different algorithms for different traffic loads.



(a) Multiple attempt.



(b) Single attempt.

Figure 5.5: Network utilization with different schemes.

The network reaches the highest utilization level using W-RWA algorithm for all traffic loads.

Although W-RWA exploits the benefit of considering different paths, it does not require significantly longer paths than shortest-path based approaches. Results for average lightpath length are shown in Figure 5.6. FWIA approach is susceptible to network load in terms of lightpath length. W-RWA and SP-BB have similar average lightpath lengths. The general tendency of average-length decrease for higher loads occurs because of decreasing performance. The algorithms fail to establish lightpaths with longer paths for higher loads. Shortest-path based FWIA and SP-BB approaches have different average lightpath lengths because the shortest-path algorithm is modified to find the shortest path that has at least one available wavelength. The difference comes

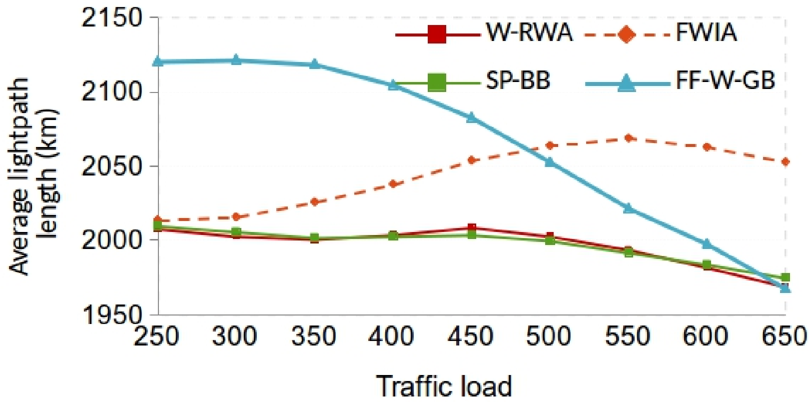


Figure 5.6: Average length of established lightpaths.

from lightpath establishment performances of algorithms. The FF-W-GB approach uses hop-count to find the appropriate path.

We also evaluated the average hop-count of established lightpaths (Figure 5.7). Each hop means an assigned wavelength on a link. Thus, this metric gives an idea about the performance of the algorithms in terms of network resource consumption. Since FF-W-GB uses hop-count to find shortest path, this algorithm shows better

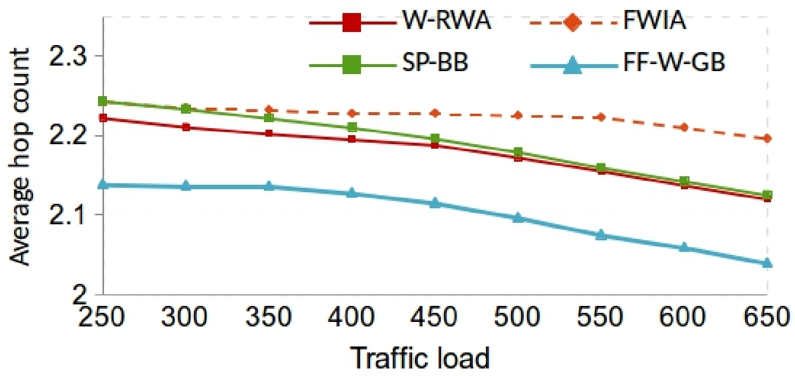


Figure 5.7: Average hop-count of established lightpaths.

performance than the others. The W-RWA algorithm shows better performance than SP-BB for low loads and similar performance with SP-BB for high traffic loads. W-RWA takes advantage of evaluating more than one path from source to destination, where those paths may have less total weight than the shortest path. Although FWIA gives close performance with SP-BB for low traffic loads, it is more susceptible to traffic load. When we consider Figures 5.7 and 5.3 together, we observe that while increasing the performance in terms of blocking, SP-BB uses more network resources than W-RWA in terms of wavelength-links.

All the algorithms are using the BER estimation model given in Section 2.3, W-RWA makes additional BER calculation only when more than one path may have the same total weight value. Let *w* be the number of wavelengths, then W-RWA makes *w* times BER calculation for the worst case. This happens at the beginning, when the network is empty. SP-BB algorithm makes *w* times BER calculations for the worst case. In average cases, SP-BB makes BER calculations for all wavelengths on the selected path. These extra calculations bring computational burden. Figure 5.8 shows the average number of BER calculations per connection request. FWIA does not look for the best BER valued wavelength, thus it makes much less BER calculation per connection request. Since there are more available wavelengths for lower traffic loads, algorithms

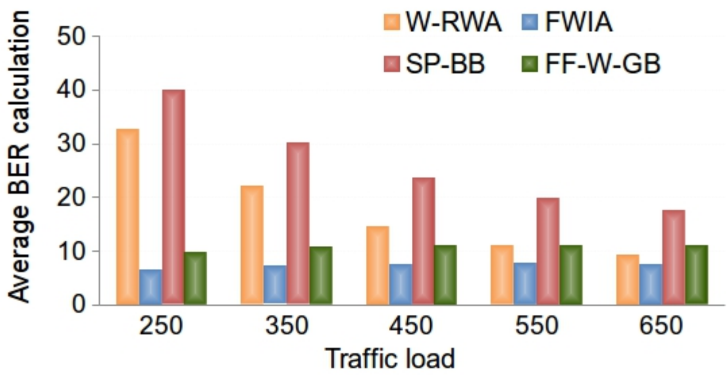


Figure 5.8: Average BER calculations per connection request.

make more BER calculation at the beginning.

Simulation times for different algorithms show that FWIA approach takes less time than others. Figure 5.9 shows the time that is spent for one connection request by algorithms in same simulation environment. Considering the blocking and the

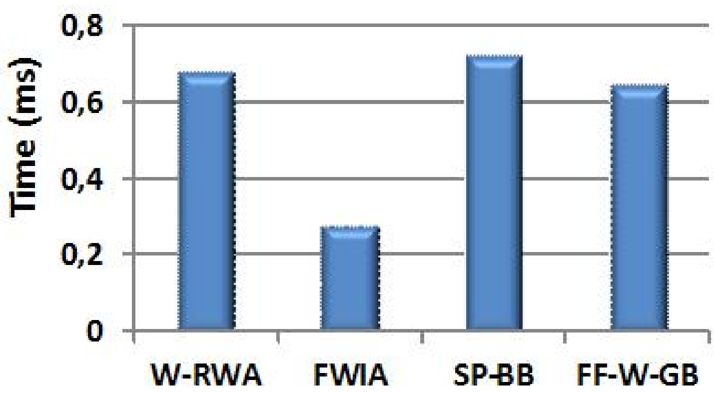


Figure 5.9: Time spent per connection request.

computational time performance, we observe that FWIA is a practical approach, especially for low traffic loads.

We also evaluated the W-RWA approach with and without *same modulation promotion*. This amendment brings up to 0.8% improvement in blocking performance to the proposed algorithm, which might be considered as minor.

5.4 Conclusion

In this chapter, we investigated the impairment-aware lightpath provisioning problem in MLR networks. In our MLR model, the nodes are capable to operate at 10, 40, and 100 Gbps, which require OOK, DQPSK, and DP-QPSK modulations, respectively. We proposed two different approaches (W-RWA and FWIA) for the problem. The FWIA partitions all wavelengths into groups, and assigns each group of wavelengths to a different line rate. The W-RWA is based on an auxiliary graph which is constructed and updated according to PLIs, and the current state of the network.

Our algorithms are evaluated through simulations and compared with other methods. The results of the simulations indicate that W-RWA outperforms others in terms of BBR and pure blocking performance. Network utilization reaches maximum level using W-RWA. We also evaluated the average length of lightpaths, and observed that the W-RWA scheme selects slightly longer lightpaths to assure better signal quality. Resource usage of the W-RWA algorithm is similar to shortest-path based approaches in terms of wavelength-links. Overall, the performance of the W-RWA algorithm and its success in making a part of the calculations off-line for on-line provisioning makes it superior to others. The FWIA is a practical approach to consider PLIs implicitly. It shows good performance, especially for lowly loaded networks, and its computational burden is considerably lower than the others.

6. LAUNCH POWER DETERMINATION

6.1 Introduction

In optical transmission, launch power is the one of the main parameters that affects the signal quality at the receiver side. Increasing the launch power results in higher resilience to noise, but it does not guarantee to improve the signal quality due to the non-linear effects, i.e., the signal with high power will be distorted by fiber dispersion and fiber Kerr nonlinearity (see Section 2.2). Increasing the power of a signal also increases the linear and non-linear crosstalk on neighboring wavelengths. Therefore, on a transparent optical path, the quality of the signal at the receiver site is dependent on the launch powers of both the actual and the neighboring signals.

In this study, we investigate the problem of launch power determination for dynamic connection provisioning in MLR networks. We propose two novel launch power determination algorithms aimed at maximizing the number of established connections. Our approaches consider the current state of the network and are PLI-aware. In Worst-case Best-case Average (WBA), average value of optical reaches are computed for worst and best cases, and used for launch power determination. In worst case, the impairments induced by other lightpaths are at the highest level, and in best case, the actual lightpath is not affected by any other lightpath. In Impairment-Aware Launch Power Determination (I-ALPD), impairments along the path are considered in a practical way to determine the launch power. The I-ALPD tracks the current state of the network, and assigns weight values to the wavelengths according to the impairments. The same auxiliary graph given in Chapter 5 is used to capture the PLIs on each wavelength with the same weight assignment scheme. The I-ALPD determines the launch power of the lightpath dynamically by comparing the total weight on the selected path-wavelength with the weight thresholds.

6.2 Related Works

Various studies have been reported on the design of MLR networks considering static traffic (see Section 3.2), but there are only a few studies on the launch power determination problem.

In [38], the authors propose a dynamic launch power control algorithm for MLR networks. In order to guarantee acceptable QoT for each lightpath, appropriate launch power is determined dynamically. They also investigate the optimum launch power margin that helps to avoid QoT violations caused by interference of future requests. The algorithm searches for appropriate launch power sequentially, starting from minimum power value, until an acceptable BER is obtained.

In [51], the authors propose a dynamic launch power control algorithm that adjusts the source power of certain channels upon the arrival of a new lightpath request. All source powers are allowed to be adjusted, even after the lightpaths have been admitted to the network and along the path. In the proposed model, all OXCs communicate with a Network Management System (NMS) upon arrival of a connection request. NMS starts the power adjustment procedure, and decides whether to establish the lightpath with a minimum or a larger initial power. The power of a certain channel can be increased on a part of a route by raising the clamping levels of the equalizers, or on the entire route.

In [52], the authors use a global optimization algorithm to find the optimum launch powers and dispersion map of a single channel at various line rates.

In [53], the authors present a sensitivity study on how launch optical power can be managed to control the capital expenditure (CAPEX) of a MLR network. The authors investigate how the network cost (in terms of transceiver costs) varies with different traffic volumes to determine an optimal combination of launch power that can lead to the lowest network cost. The cost of capacity follows volume discount as the cost scales up nonlinearly with capacity. It is observed in the study that the network cost is a sensitive function of traffic and power variation, i.e., if 10G lightpaths are established with lower launch powers, more volume discount can be exploited, as more high-bit-rate lightpaths can be accommodated.

In [54], the authors address the RWA problem from the energy consumption point of view considering a single-line-rate network. They investigate the optimum path and wavelength leading to minimum power consumption.

Not only the launch power of the actual signal, but also the launch power of neighboring lighpaths affect the signal quality at the receiver. In [55], the authors present the crosstalk effect of neighboring OOK channels over DQPSK channels. The results show that a single OOK channel has a slight crosstalk effect on an adjacent 40G channel, but even this slight effect may degrade the overall performance. On the other hand, XPM effect of adjacent OOK channels is more severe.

The authors in [18] presented a theoretical model for the influence of XPM induced non-linear phase noise from copropogating OOK channels. The XPM effects of neighboring OOK signals are dependent on its launch power.

In [5] and [34], the authors present the effects of copropogating 10G, 40G, and 100G to each other, on a field-deployed fiber. The results presented in [5] indicate that, 100G channels are highly susceptible to launch power of neighboring channels. They suffer from XPM and linear crosstalk effects of copropogating channels. Especially, 10G channels have strong XPM influence on 100G channels, and this influence can be significantly reduced by carefully choosing the launch power of the neighboring channels. The performance of 40G channels also degrades due to both XPM and linear crosstalk effects.

Our study is one of the few dealing with PLI-aware lightpath provisioning with launch power determination. We propose two practical and efficient approaches, which consider the current state of the impairments, and determine launch powers dynamically. As a launch power determination algorithm, our approaches make BER calculation only for the determined launch power, not for all possible launch power values. Thus, our approaches do not bring additional computational burden and are easy to implement.

6.3 Effects of Launch Power

The effects of the launch power are examined through a study using the BER evaluation model given above. In this study, lightpath provisioning performance is evaluated with different launch powers (discrete values between -3 dBm and 3 dBm) for different line rates (10G, 40G, and 100G). For each run of the simulation, launch power of a single line rate is altered while launch power of the others are kept the same.

Shortest-path, first-fit (SP-FF[1]) algorithm is used to evaluate the performance. Same amount of traffic load (≈50% utilization) is offered to the network for each run of the simulation. Other system parameters are given in Appendix A.

The results of the study indicate that increasing the launch power increases the resilience to noise and gives better performance. On the other hand, increasing the launch power of a line rate decreases the lightpath provisioning performance of the other line rates. DP-QPSK modulated channels with 100G line rate are more susceptible to launch power of neighboring lightpaths, especially OOK channels. Using the system parameters given in Appendix A, from blocking probability point of view, the best performing (inducing minimum blocking ratio) combination of initial powers is obtained as -2, 0, 2 dBm for 10G, 40G, and 100G, respectively. Worst performing launch power combination, in terms of blocking probability and system throughput is obtained as 2, -3, -3 dBm for 10G, 40G, and 100G, respectively.

Figure 6.1 shows the blocking ratio of two different line rates (40G and 100G) with different launch powers on NSFNET. In Figure 6.1, launch powers of 10G lightpaths are kept fixed (0 dBm) during simulation, and launch powers of 40G and 100G are altered from -3 dBm to 3 dBm.

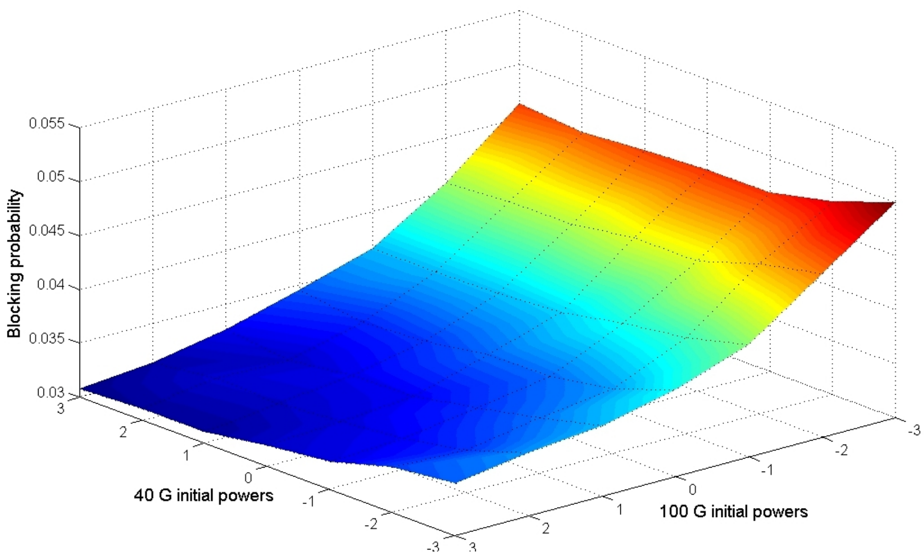


Figure 6.1: Blocking probability change according to launch power variation.

[1] SP-FF chooses the first available wavelength on shortest path.

The results of this study and the other studies in the literature indicate that detrimental effects of PLIs induced by neighboring lightpaths can be significantly reduced by carefully choosing appropriate launch powers. PLI-aware approaches are needed to determine the launch power of lightpaths in MLR networks. Due to the dynamic nature of lightpath provisioning, the proposed approaches should be dynamic and easy to implement. The proposed algorithms are given in the following sections.

6.4 Launch Power Determination Algorithms

In this chapter, we investigate the launch power determination problem of impairment-aware dynamic lightpath provisioning. The problem defined in Section 3.3 is added a new dimention, and the goal becomes:

- Route over which the lightpath should be set up,
- Wavelength to be assigned, and
- Launch power to establish the lightpath for the requested connection.

We propose two different algorithms to determine the launch power of a lightpath, in MLR networks: Worst-case Best-case Average (WBA) and Impairment-Aware Launch Power Determination (I-ALPD). The details of algorithms are discussed in the following subsections.

6.4.1 Worst-case best-case average (WBA)

WBA scheme takes impairments into consideration in an average manner. It calculates the optical reaches for best and worst conditions, in terms of impairments, and uses the average of reach values to compare with the length of the candidate lightpath. For 40G (and 100G), worst-case scenario occurs when the central wavelength is occupied by the 40G (or 100G) signal while all the other wavelengths are occupied by 10G OOK signals, along the path. In worst-case scenario, the neighboring OOK signals have the highest possible launch power. For OOK signals in worst-case scenario, neighboring wavelengths are occupied with signals having the highest possible launch power. Best-case scenario is same for all line rates, i.e., the network is empty. This approach provides a simple approximation for medium loaded networks. It is easy to implement, and it doesn't bring computational burden. The WBA algorithm is given in Algorithm 4. Before any request comes, the reaches for both (worst, best) cases

Algorithm 4 WBA algorithm.

1. Prior to any connection request, find the optical reaches for worst and best cases, and constitute an average-reach table. After a connection request comes, and RWA algorithm finds a candidate lightpath.
2. Get the length of the candidate lightpath.
3. Look up the average-reach table to find the appropriate power.
   - Go down to the requested line rate.
   - Search for the closest reach value to the lightpath length in this row.
   - Select the matching power value.
4. If the candidate lightpath is accepted after BER evaluation, establish lightpath.

are calculated for each launch power value (in our case, from -3 dBm to 3 dBm). The average of best and worst cases is calculated, and these average-reach ($R_a^{P_{ch}}$) values are kept in a table (i.e., Table 6.1). When a request comes, first the RWA algorithm finds a path from source s to destination d, and then, WBA determines the launch power. In WBA, starting from the minimum power option ($P_{ch}(Min)$), the differences between path length and average reach are examined, and the power value having the minimum difference between average reach and path length is selected:

$$Min_{P_{ch}(Min-Max)}(\mid L_{sd} - R_a^{P_{ch}} \mid) \qquad \textbf{(6.1)}$$

where L_{sd} is the length of the path, and $R_a^{P_{ch}}$ is the average reach with launch power P_{ch}.

The algorithm examines the average-reach values sequentially, and finds the closest one to the path length, i.e., for a connection request with 40G line rate, let the length of the path from s to d be 2100 km. Given Table 6.1, since the path-length average-reach difference for -2dBm ($|2000-2100|$) is smaller than the difference for other power values (i.e., for -1dBm $|2500-2100|$), -2 dBm is selected.

WBA algorithm constitutes the reach table before any request comes and it starts working after the candidate lightpath is found. Apart from RWA algorithm, let P be

Table 6.1: Sample average-reach table.

	-3	-2	-1	0	1	2	3 (dBm)
Line Rate	**Average reach** (km)						
10G	2200	2800	3200	3600	4100	4200	4200
40G	1500	2000	2500	3000	3500	4000	4000
100G	800	1000	1200	1400	1600	1800	1800

the number of available launch powers, and R be the number of line rates, then finding the appropriate launch power from the average-reach table has $O(R+P)$ complexity.

6.4.2 Impairment-aware launch power determination (I-ALPD)

The I-ALPD algorithm keeps track of impairments on each wavelength-link, and assigns weight values to the wavelengths according to the impairments. I-ALPD determines the launch power of the lightpath according to the total weight accumulated along the path on the selected wavelength. An auxiliary graph $G(V,E)$ (Figure 5.2) is used to monitor and track the current state of impairments. Auxiliary graph construction is given in Section 5.2. The weight-assignment scheme given in Section 5.2 is used to capture the PLIs. The weight values represent linear and non-linear impairments that occur on the physical links (ASE, losses, and SPM), and on the nodes (XT and losses). Weights are increased when a lightpath is established, and decreased when the lightpath is torn down. The weight assignment process can be made off-line, using the idle time between dynamic connection requests.

In I-ALPD, launch power is determined according to accumulated impairments along the selected path. After finding the appropriate path and wavelength from source to destination, the total weight on this path is calculated. I-ALPD algorithm is given in Algorithm 5.

Total-weight thresholds (i.e., Table 6.2) are used to determine the launch power of the lightpath. The algorithm examines the weight thresholds, and finds the closest one to the total weight on the selected path, i.e., for a connection request with 40G line rate, let the weight on selected path from s to d be 0.5. Since $|0.4-0.5| < |0.7-0.5|$, -1 dBm is selected.

I-ALPD algorithm calculates the total weight along the path in linear time, $O(E_{LP})$, where E_{LP} denotes the edges of the candidate lightpath. Since weight caused by

Algorithm 5 I-ALPD algorithm.

1. Update the auxiliary graph according to existing lightpaths.
2. Calculate the total weight on candidate lightpath.
3. Look up the thresholds table to find the appropriate power.
    - Go down to the requested line rate.
    - Search for the closest threshold value in this row.
    - Select the matching power value.
4. If the candidate lightpath is accepted after BER evaluation,
    - Establish the lightpath.
    - Update the auxiliary graph.

Table 6.2: Sample weight thresholds.

	-3	**-2**	**-1**	**0**	**1**	**2**	**3 (dBm)**
Line Rate	**Weight Thresholds**						
10G	0	0.5	1	2	3	4	5
40G	0	0.2	0.4	0.7	1	2	3
100G	0	0.1	0.2	0.4	0.6	0.8	1

vertex *j* is accounted with the edge *i,j* for specific wavelength λ, only edge weights are considered. Let *P* be the number of available launch powers, and *R* be the number of line rates, then finding the appropriate launch power from the weight threshold table has *O(R+P)* complexity. The main computational burden of this algorithm is to update the auxiliary graph with complexity of $O((2 \times GB \times R \times E_{LP}) + (N \times V_{LP}))$, where $2 \times GB$ denotes the affected wavelengths, and *N* denotes the number of ports at each vertex. On the other hand, auxiliary graph, which is referred for on-line connection requests is updated off-line, after a lightpath is established or released.

6.5 Illustrative Numerical Examples

In this study, we consider an optical WDM network in which each node can support transmission at 10, 40, and 100 Gbps. NSFNET and EON (see Appendix B) are used to evaluate the performance of the proposed schemes. In our network model, all nodes are assumed to have adjusting launch power capability, but power sources are not allowed to be adjusted after establishing the lightpaths. Once the lightpath is established, its launch power stays still during its lifetime. Physical links are assumed to have inline (EDFA) amplifiers at every 82 km, with 70 km standard single mode fiber, and 12 km dispersion compensation fiber. We considered 50-GHz spacing with 80 wavelengths.

Least congested path (LCP)-First Fit (FF) is used to find the appropriate path and wavelength. The LCP method is a modified version of LCP algorithm introduced in [44]. The algorithm first finds *n*-shortest paths [45], and then selects the path that has the maximum number of available wavelengths. FF selects the first available wavelength on the selected path. Wavelength continuity constraint is applied for intermediate nodes. Launch power of this candidate lightpath is determined using one of the launch power determination algorithms. BER evaluation is made to see whether the candidate lightpath meets the minimum BER requirement with the selected launch power. Signal quality of the existing lightpaths, which is affected from the candidate lightpath, are examined before establishing the candidate lightpath. If the candidate lightpath damages the signal quality of any existing lightpath and forces it to have an unacceptable BER value, the lightpath is not established, and the connection request is rejected.

The connection requests arrive according to Poisson distribution with exponentially-distributed holding times, and they are uniformly chosen among 10G, 40G, and 100G. The traffic load is given in Erlangs. We ran the simulations for one million connection requests. Discrete values from -3 dBm to 3 dBm are used for launch powers. Other system parameters are given in Table A.2.

We compared our approaches with existing dynamic and fixed power approaches. Dynamic power control (DPC) is a dynamic impairment-aware launch power determination approach, which is a modified version of the algorithm proposed in [38]. DPC searches for appropriate launch power sequentially starting with the possible minimum launch power, which is -3 dBm in this study. If the given launch power is not sufficient to establish a lightpath, the algorithm increases the launch power by minimum unit. This search goes up to maximum allowed launch power, which is 3 dBm in this study. The search ends either with finding the appropriate launch power for the lightpath or reaching the maximum allowed launch power. We also compared our approaches with Fixed Launch Power (FLP) approach, where launch powers are fixed for all alightpaths. We used 0 dBm for FLP, which is the median of power values (-3 to 3 dBm) used in this study.

An incoming request can be rejected due to insufficient network resources (*resource blocking*) or to PLIs (*physical-layer blocking*) [1]. LCP-FF algorithm finds an appropriate path and wavelength first. If the algorithm cannot find an appropriate path-wavelength pair, then the connection request is rejected due to resource blocking. After finding an appropriate path-wavelength pair, the candidate lightpath is evaluated for signal quality using the BER estimation model given in Section 2.3.2. If the signal quality is not good enough to establish this lightpath, then the connection request is rejected due to physical-layer blocking. We evaluated the physical-layer blocking performance of the algorithms separately to study the effects of launch power.

Figure 6.2 shows the blocking ratio due to PLIs for NSFNET; the blocking ratio due to insufficient network resources is not shown in this figure. Impairments induced

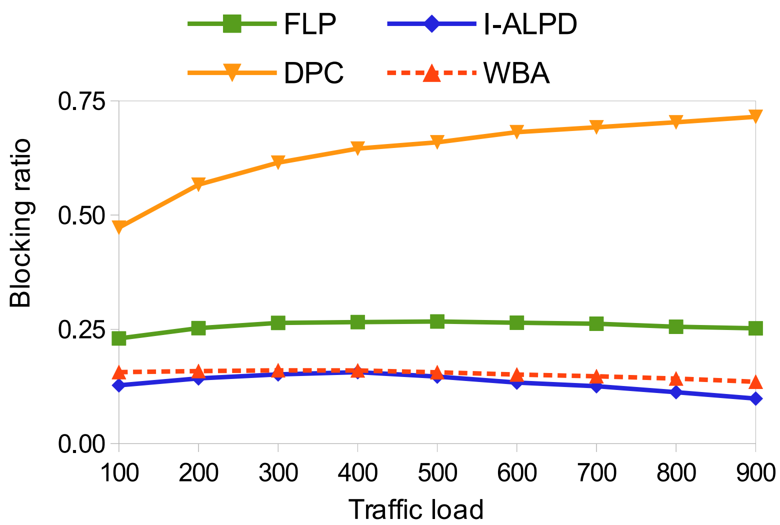


Figure 6.2: Blocking ratio due to PLIs (NSFNET).

by established lightpaths increase in parallel with increasing traffic load; thus, the physical-layer blocking ratio increases for all algorithms. For medium and high traffic loads, resource blocking becomes higher (see also Fig. 6.4), and blocking ratio due to PLIs decreases (see also Fig. 6.3).

The proposed algorithms show better blocking probability performance than the others. I-ALPD gives better results than WBA. DPC method has more blocking ratio than others. There are two main reasons for high blocking ratio of DPC. The first reason is the lightpaths established with high launch powers. DPC tries to establish each lightpath with minimum required launch power, but the search can go up to maximum allowed launch power. Each lightpath with high launch power, especially the OOK channels, affects other lightpaths and degrades the overall performance. The other reason is that the candidate lightpaths are not allowed to be established if they disrupt the existing lightpaths.

Figure 6.3 shows the blocking ratio due to PLIs for EON topology. EON has shorter

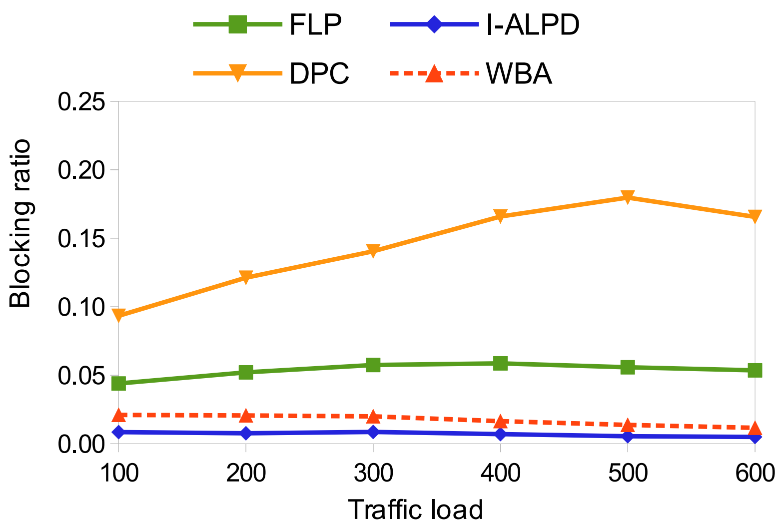
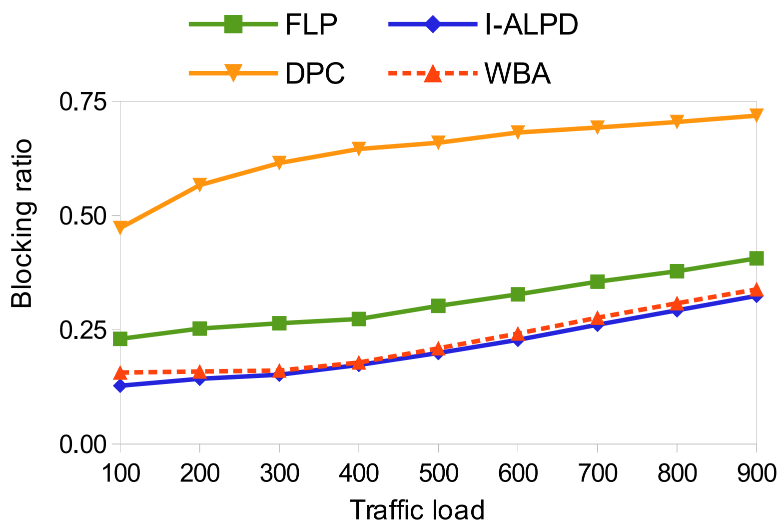


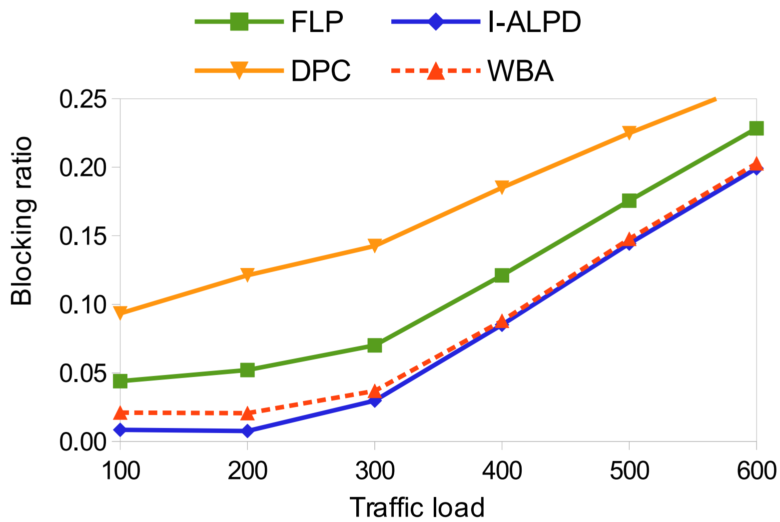
Figure 6.3: Blocking ratio due to PLIs (EON topology).

link distances than NSFNET; thus, the blocking ratio due to PLIs for EON is lower than for NSFNET. On the other hand, EON has more number of nodes than NSFNET, with less average node degree, which causes the average hop count being higher than NSFNET. EON has also smaller connectivity than NSFNET. Increasing average hop count of paths increases linear XT, on the other hand increasing average hop count in this topology decreases the network resources in terms of wavelength-links; thus, resource blocking becomes higher for medium and high traffic loads (see also Fig. 6.4) and blocking ratio due to PLIs decreases. I-ALPD experience lower blocking probability than others. The blocking ratio differs with this topology but the performance of algorithms doesn't change.

Figure 6.4 shows the total (physical-layer and resource) blocking ratio for different schemes for different topologies. Again, I-ALPD experiences lower blocking probability than the other approaches for both topologies. The performances get closer with increasing traffic load. This is because resource blocking becomes the dominant factor for medium and high traffic. WBA shows better performance than both FLP and



(a) NSFNET.

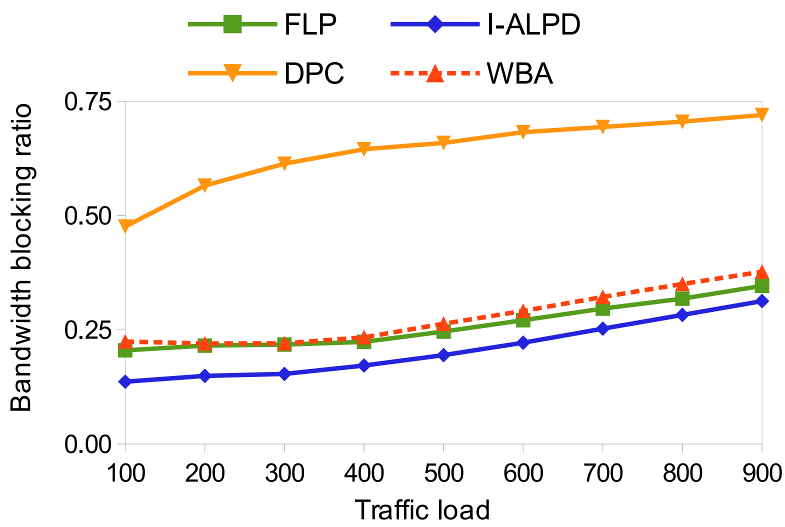


(b) EON topology.

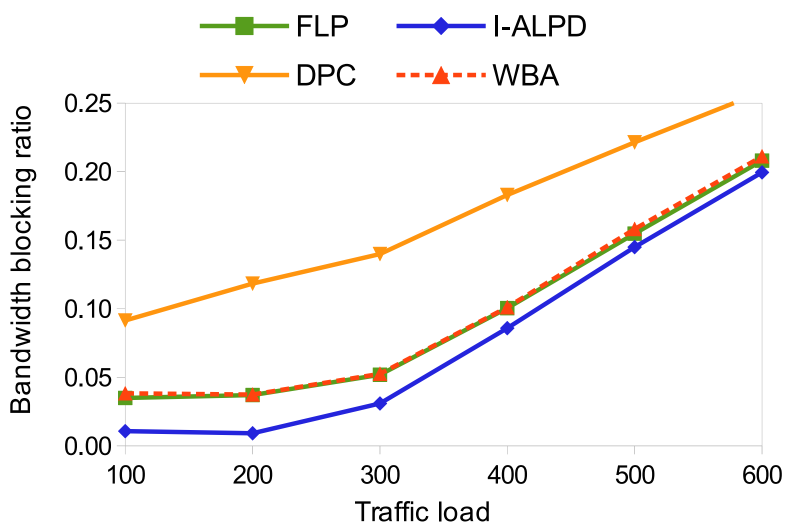
Figure 6.4: Total (physical-layer and resource) blocking ratio of proposed schemes for different topologies.

DPC. All approaches have low blocking ratio for low traffic loads in EON topology, but they all experience performance decrease with increasing traffic due to large resource blocking.

Figure 6.5 shows the BBR for different lightpath provisioning schemes with uniformly distributed connection requests. The algorithms show similar performances with total blocking ratio performance for both topologies. I-ALPD experiences lower bandwidth blocking ratio than the other approaches. In I-ALPD, weight threshold values for each line rate are different, and it helps to give priority for higher line rate. The performances of WBA and FLP are close to each other for all traffic loads, and they



(a) NSFNET.



(b) EON topology.

Figure 6.5: Bandwidth blocking ratio of proposed schemes for different topologies.

have the average performances. Increasing impairments decrease the performance of WBA, because WBA is based on the average value which can be considered as the equivalent of medium traffic load.

The algorithms FLP, WBA, and I-ALPD make BER calculations only once for each connection request. If the obtained BER is acceptable, then the lightpath is established. In DPC, BER estimation can be made more than once for different launch powers. To evaluate the computational burden of the algorithms, we monitored the BER calculation of algorithms.

Figure 6.6 shows the average BER calculations to establish a single lightpath. The results are obtained by dividing the number of BER calculations to number of established lightpaths.

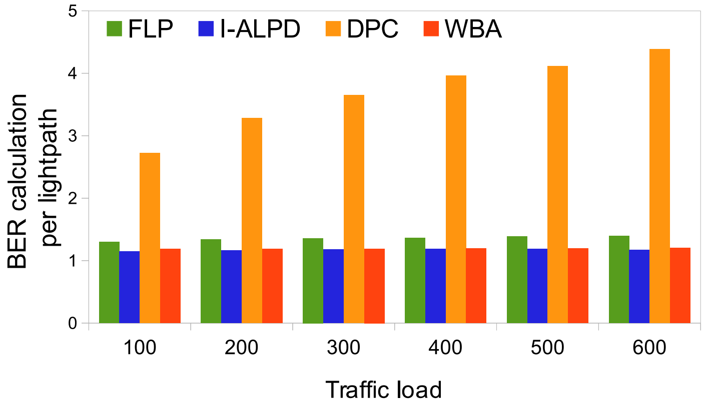


Figure 6.6: BER calculation per lightpath.

The differences between FLP, WBA, and I-ALPD are not significant, but DPC makes two or more times more BER calculation than the other algorithms per connection request. Number of BER calculations per connection request increases with increasing utilization for DPC. Figure 6.7 shows the average time consumption of algorithms

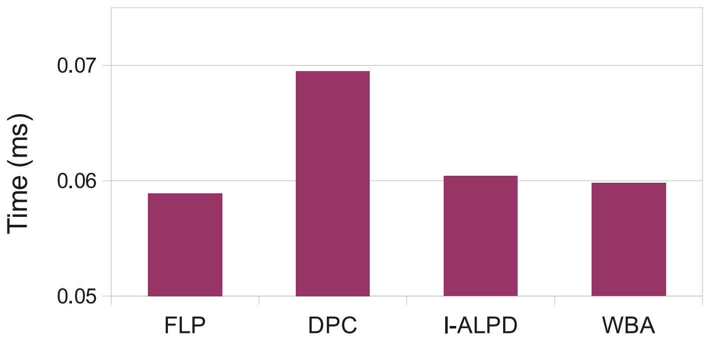


Figure 6.7: Simulation time per connection request.

per connection request in the same simulation environment. Simulation times for algorithms show that FLP takes less time than others. DPC spends more time than others, and I-ALPD takes slightly more time than FLP. While implementing on real networks, I-ALPD can use idle times between connection requests to update the auxiliary graph, but this figure includes the weight assignment times as well. WBA shows slightly better results than I-ALPD in terms of simulation time.

6.6 Conclusion

Signal quality at the receiver side depends on many factors, including launch power of the actual signal, neighbouring signals, modulation technique, path length, etc. Enhancing one of these parameters cannot be a proper way to get better signal quality. In this chapter, we examined the effects of launch power on the signal quality in optical MLR networks. The effects of the launch power cannot be isolated from other parameters, but still blocking ratio performance can be improved by selecting appropriate launch powers.

We proposed two heuristic approaches to select the appropriate launch power for dynamic connection requests: Worst-Case Best-Case Average (WBA) and Impairment-Aware Launch Power Determination (I-ALPD). To determine the appropriate launch power, WBA uses the optical reaches for highest possible impairment (worst-case) and without impairment (best-case) scenarios. I-ALPD considers the instantaneous state of the network, and assigns weight values to the wavelengths in accordance with the impairments. By comparing the weights on the selected path-wavelength with the weight thresholds, I-ALPD determines the launch power of the lightpath dynamically. The proposed algorithms are evaluated through simulations, and compared with dynamic power control and fixed launch power approaches. Our results indicate that I-ALPD outperforms the other approaches, in terms of blocking probability and bandwidth blocking ratio.

7. CONCLUSION

In this thesis, we investigated impairment-aware (IA) lightpath provisioning problem in MLR networks. IA lightpath provisioning is a cross-layer optimization problem which aims to maximize the established connections at the network layer, and assures signal quality at the physical layer. In optical transmission, a signal undergoes various physical-layer impairments, and its quality degrades as it travels. In MLR networks, advanced modulation techniques (i.e., DQPSK, DP-QPSK) are required for high line rates, and these modulation techniques are highly susceptible to PLIs, therefore there is a trade-off between capacity and signal quality. Moreover, in MLR networks, coexistence of OOK signals with advanced modulation formats induces higher XPM. Accounting for PLIs during the provisioning phase, which is an important problem in single-line-rate WDM networks, acquires even larger importance in MLR networks.

We first investigated the effects of inverse multiplexing (IM), which is a technique that tries to exploit the advantage of transmitting the signals with low line rates, where the high line rate is not possible due to impairments. We proposed various approaches (SP-BB, SP-MSD, MH-BB, MH-MSD, LCP-BB, and LCP-MSD) employing IM for the problem. The proposed schemes use *shortest path*, *minimum hop*, and *least congested path* algorithms to find the appropriate path. Wavelength assignment is done according to *best-BER* or *maximum spectral distance* approaches. IM is employed where high line rates are not feasible due to PLIs. Our algorithms are evaluated through simulations. The results indicate that the performances of the algorithms differ according to topologies and traffic load. But in all cases, algorithms employing IM outperform the algorithms that are not employing IM in terms of blocking ratio. SP-MSD scheme shows the best blocking probability performance for all traffic loads. LCP-MSD shows good blocking probability performance for lower traffic loads, but it experiences a performance decrease with increasing traffic load. Although the MH-based schemes using IM show better performance than not using IM, their performances are below the SP and LCP-based schemes. The performance increase obtained from IM comes with a trade-off. The algorithms employing IM use more wavelength-links to accommodate the same amount of request. LCP-based algorithms employing IM experience the worst performance in terms of additional wavelength-links usage. To improve the performance in terms of blocking ratio, network operators can use adaptive schemes, which consider the resources they have and the state of the network.

We also proposed two novel approaches for the IA lightpath provisioning problem: FWIA and W-RWA. FWIA partitions the wavelengths into groups, assigns each group to a different line rate, and establishes lightpaths with different modulation formats over the assigned wavelength groups. W-RWA captures the instantaneous state of the network and assigns weight values according to affecting impairments. The algorithm tries to select the wavelengths which are less exposed to impairments while trying to leave feasible wavelengths for future requests, and avoiding damaging the existing lightpaths. Since the weight assignment process can be made off-line, W-RWA makes use of idle time before any request comes. The proposed algorithms are evaluated through simulations together with existing algorithms. The W-RWA shows better performances in terms of blocking probability and bandwidth blocking ratio than the others. We also evaluated the average length of lightpaths and the average hop count, which indicate the additional resource usage in terms of wavelength-links. Our results indicate that W-RWA selects slightly longer lightpaths to assure better signal quality. Resource usage of W-RWA is similar to shortest-path-based approaches in terms of hop count. Overall, the performance of W-RWA and its success in making a part of the calculations off-line for on-line provisioning makes it superior to others. FWIA algorithm seems to be a practical approach to consider PLIs implicitly. It shows good performance, especially for lightly loaded networks, and its computational burden is considerably lower than others.

Another important parameter for signal quality is the launch power of both the actual signal and the neighboring signals. In this study, we also evaluated the effects of launch power, and proposed two practical approaches to determine appropriate launch power. In WBA, average optical reach for worst and best cases, in terms of impairments, is used to determine the launch power. In I-ALPD, impairments along the path are considered in a practical way to determine the launch power. I-ALPD tracks the current state of the network, and assigns weight values to the wavelengths according to the impairments. I-ALPD uses an auxiliary graph to capture the PLIs on channels with a weight assignment scheme. The proposed algorithms are evaluated through simulations, and compared with dynamic power control and fixed launch power approaches. Our results indicate that I-ALPD outperforms the other approaches, in terms of blocking probability and bandwidth blocking ratio. We observed that the network performance, in terms of blocking probability, can be improved by selecting appropriate launch powers for lightpaths, considering the current state of the network.

This study is one of the few dealing with the dynamic impairment-aware lightpath provisioning problem in MLR networks. The proposed approaches show better provisioning performance than the existing ones. The proposed approaches are also easy to implement and can be adapted to the needs of the network operators. They do not bring additional computational burden. The results indicate that the success of an algorithm depends on how much it considers existing lightpaths. In such a dynamic environment, easy implementation of an algorithm is highly important. This thesis may lead to new studies on IA lightpath provisioning studies in MLR networks.

Network components enabling MLR architectures have been deployed, and modulation formats are expected to get more complex and become more susceptible to PLIs. In dynamic lightpath provisioning problem, impairment awareness can be expected to get more importance.

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APPENDICES

APPENDIX A : System Parameters

Table A.1: System parameters for impairment-aware dynamic lightpath establishment problem.

Parameters	**Value**
BER threshold	$10^{-4}, 10^{-5}$
Number of wavelengths, W	80, 40
Line Rates (Gbps)	10, 40, 100
Number of transceivers at each node	14, 13, 13
Signal Launch power (mW)	1
Gain of EDFA (G_{in}, G_{out})(dB)	20.8, 19
Amplifier Noise Factor (F)(dB)	4
Fiber loss factor, $\alpha_{SMF}, \alpha_{DCF}(dB/km)$	0.2, 0.6
Dispersion P., D_{SMF}, D_{DCF} ps/(km.nm)	17, 92
PMD Coefficient, $D_{PMD}\ ps/\sqrt{km}$	0.2
$L_{SW}, L_{DMX}, L_{MX}, L_{tap}$ (dB)	5, 5.5, 4.5, 1
X_{SW}, X_{DMX}, X_{MX} (dB)	-45, -25,-25
Symbol Time (10,40,100) (ps)	100, 50, 40
Kerr Coefficient, n_2 (m^2/W)	3
$A_{eff}SMF$, $A_{eff}DCF$ (μm^2)	80, 30
Filtering Effect (K_{DQPSK}, K_{QPSK})	1, 7
$\omega^{\lambda}_{XT_a}, \omega^{\lambda}_{XT_b}$	0.05, 0.01
ω^{λ}_{SPM}, ω^{r}_{XPM}	0.1, 0.5
ω^{λ}_{CD}, ω^{λ}_{ASE}	0.4, 1
κ, ζ, Ξ	0.01, 0.5, 0.05

Table A.2: System parameters for launch power detemination problem.

Parameters	**Value**
BER threshold	10^{-4}
Reference launch powers (10,40,100G)	-2, 0, 2
Weight thresholds (10G) ($W^{th,lower}_{OOK}, W^{th,upper}_{OOK}$)	0.3, 3
Weight thresholds (40G) ($W^{th,lower}_{DQPSK}, W^{th,upper}_{DQPSK}$)	0.3, 1.8
Weight thresholds (100G) ($W^{th,lower}_{DP-QPSK}, W^{th,upper}_{DP-QPSK}$)	0.2, 0.4
$\omega^{\lambda}_{XT_a}, \omega^{\lambda}_{XT_b}$	0.2, 0.1
ω_{XPM}	1

APPENDIX B : Topologies

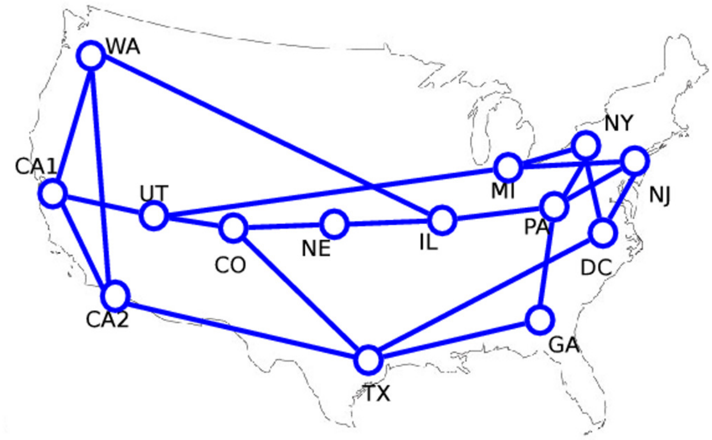


Figure B.1: NSFNET topology.

NSFNET topology has 14 nodes and 21 links. The average link distance is ≈930 km.

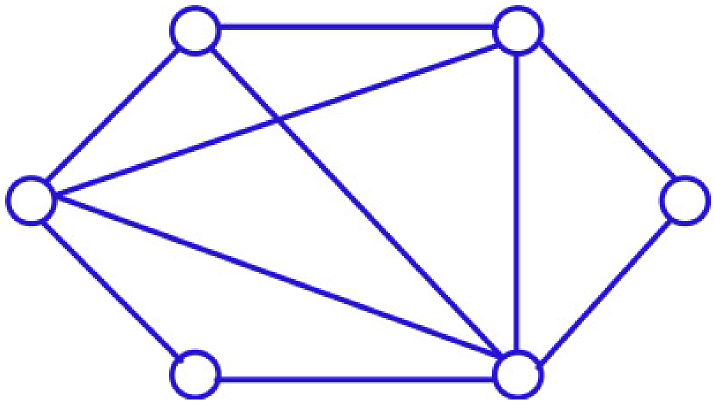


Figure B.2: 6-Node topology.

6-Node topology has 6 nodes and 10 links. The average link distance is ≈930 km.

Europian optical network (EON) topology has 28 nodes and 41 links. The average link distance is ≈550 km.

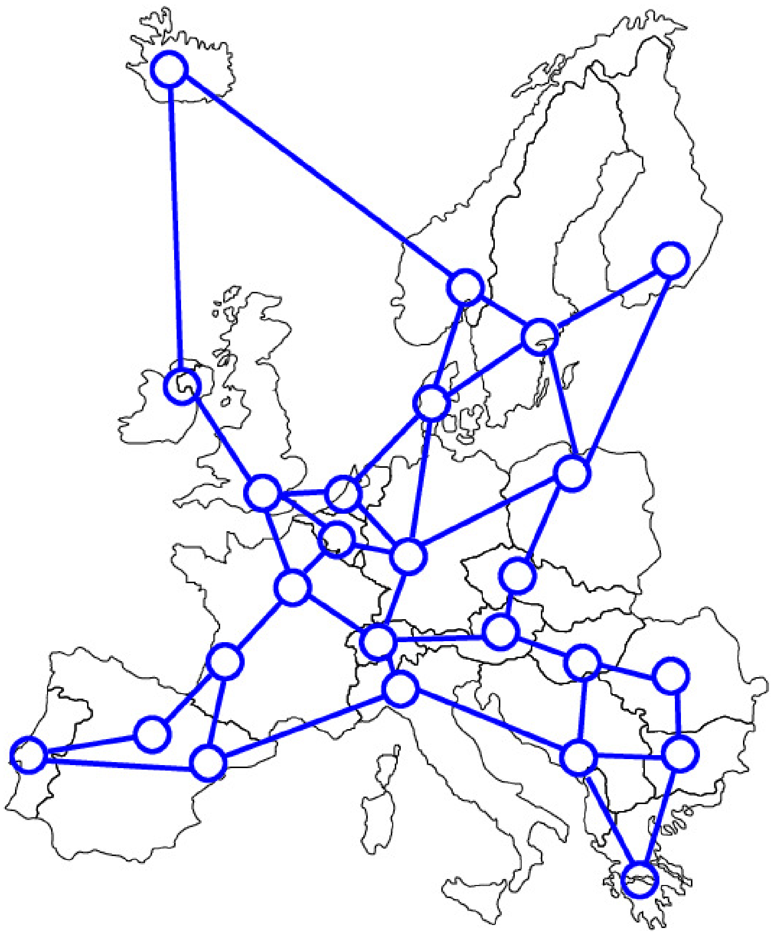


Figure B.3: European optical network topology.

APPENDIX C : Inverse Multiplexing Evaluation

In this study [50], we investigate the inverse multiplexing (IM) gain in MLR networks for the impairment-aware dynamic lightpath provisioning problem. To evaluate the performance of IM in MLR networks with dynamic traffic, we modified the Best-BER (BB) algorithm introduced in [47] using *k*-shortest path and employing IM, if needed. The algorithm is given in Algorithm 6.

Algorithm 6 Best-BER on *k*-shortest path with inverse multiplexing.

---

1. Find *k*-shortest path from *s* to *d*.
2. Find available wavelengths on the paths.
   - If a path with an available wavelength does not exist, reject the request (resource blocking).
3. Estimate BER values for all available wavelengths.
4. Sort the wavelengths in ascending order according to estimated BER values.
5. Check if the path and wavelength pair with best BER value is below acceptable BER threshold (physical-layer blocking).
   - If the estimated BER is above the threshold, than inversely multiplex the request into smaller requests.
   - Take these sub-request as new requests and run the algorithm from the beginning, for each.
   - If any of sub-requests cannot be established due to resource or physical-layer blocking, than reject the whole request.
6. Verify existing lightpaths with candidate lightpath(s).
   - If any existing lightpath becomes infeasible, reject the request (physical-layer blocking).
7. Set up the lightpath(s).
8. Release the connection(s) after holding time.

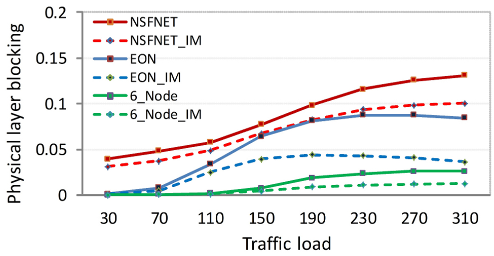
In the algorithm, k shortest paths from source (*s*) to destination (*d*) are found using *k*-shortest path algorithm. For *k*=1 the algorithm considers only the shortest path. After finding shortest path, BER value is estimated for each available wavelength on these paths. The route and wavelength pair that is expected to have the best BER is selected. If the estimated BER of the found route and wavelength exceeds the acceptable threshold, the request is inversely multiplexed into smaller requests, starting with the one level lower line rate. If the line rate of the request is the minimum, then the request is rejected. In case any sub-request is rejected, the whole request is rejected.

The algorithm also takes the existing lightpaths into account. After finding the candidate route and wavelength with acceptable BER, existing lightpaths are also verified. If any existing lightpath is weakened to have BER value more than acceptable threshold, then the candidate lightpath is not allowed to be established.

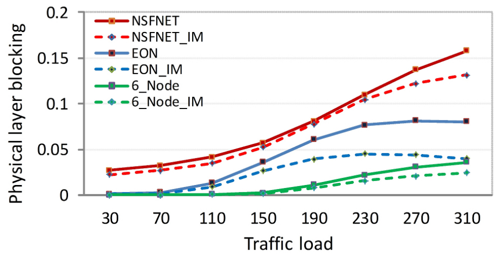
Illustrative Numerical Examples

We used the same system parameters given in Section 4 to evaluate the lightpath provisioning performance of the algorithm with and without IM.

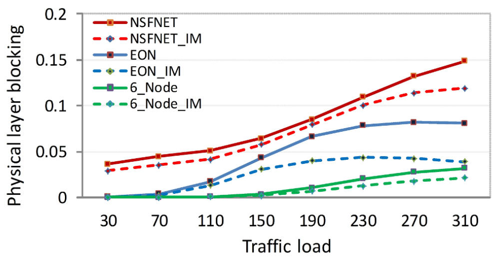
Figure C.1 shows the blocking ratio due to impairments, for both IM-employing and not employing schemes with different *k* values for *k*-shortest path.



(a) *k*=1



(b) *k*=2



(c) *k*=3

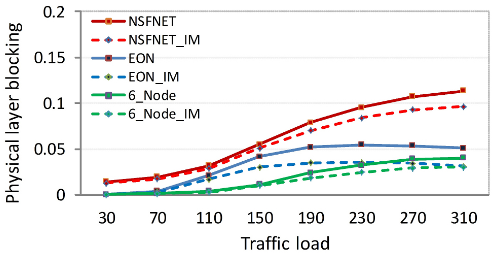
Figure C.1: Blocking ratio due to PLIs for uniform traffic.

The dashed lines indicate the IM-employing schemes. For high traffic loads, impairments induced by established lightpaths increase, thus the blocking ratio increases.

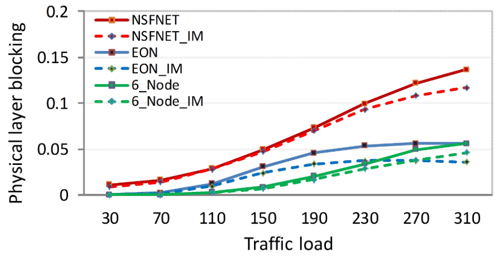
With the increase of *k* in *k*-shortest path algorithm, the algorithms find opportunity to look for appropriate route and wavelength over more than one path. On the other hand, establishing more lightpaths increases PLIs, and causes more requests to suffer from physical-layer blocking.

The results given in Figure C.1 are obtained from uniform traffic; we also evaluated the performances for skewed traffic profile. Bandwidth blocking ratio due to impairments for skewed traffic is given in Figure C.2.

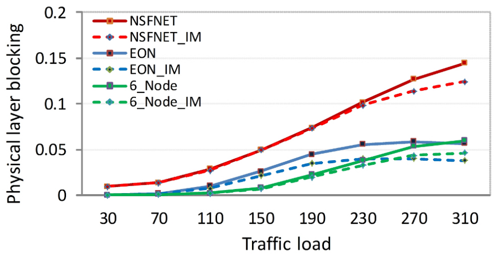
For all values of *k*, it is seen in Figure C.2 and Figure C.1 that IM increases the performance in terms of blocking due to PLIs. For high traffic loads, since the resource blocking increases, the difference between IM-employing and not employing schemes decreases. Even in some high load cases, blocking ratio due to PLIs decreases due to increasing resource blocking. Figure C.3 shows the total (physical and resource) blocking ratio for both IM-employing and not employing schemes with different *k* values for *k*-shortest path.



(a) k=1

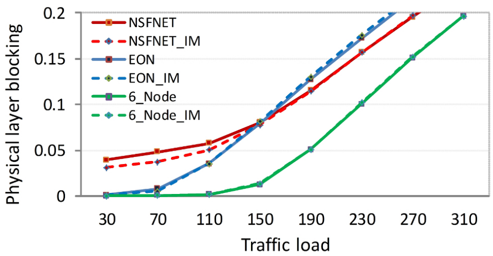


(b) k=2

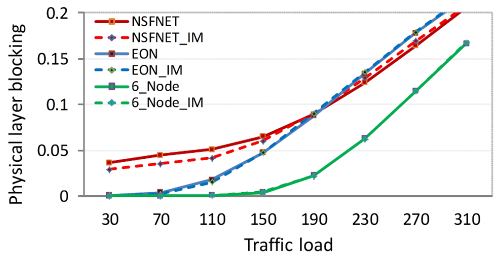


(c) k=3

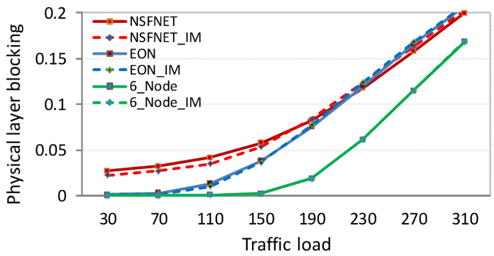
Figure C.2: Bandwidth blocking ratio due to PLIs for skewed traffic.



(a) k=1



(b) k=2

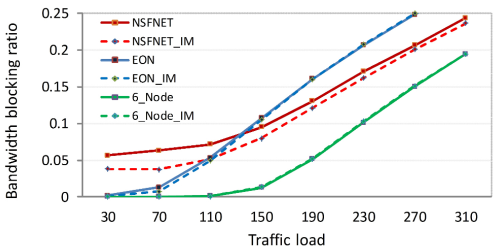


(c) k=3

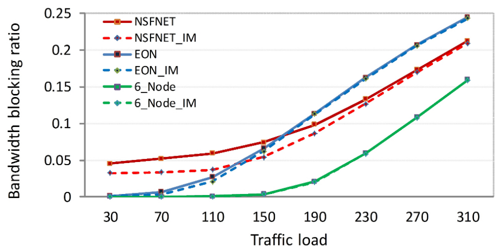
Figure C.3: Total blocking ratio for uniform traffic.

The total blocking ratio of IM-employing and not employing schemes show similar results for different topologies. In all cases, for low traffic load, the blocking ratio performance increases with IM, but when network resources do not let the algorithm to find available paths, performances come closer to each other. So, IM increases the performance of blocking due to PLIs, but it does not help to improve the performance in terms of total blocking ratio.

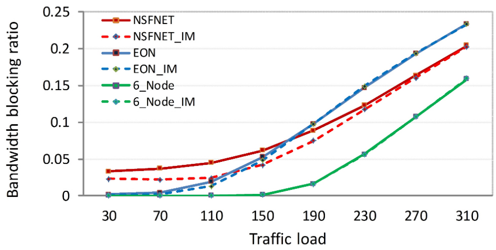
We evaluated the BBR performance of inverse multiplexing scheme. Figure C.4 shows the total BBR, for both IM-employing and not employing schemes with different k values for k-shortest path. The scheme that employs inverse multiplexing slightly improves the performance up to a utilization level ($\approx 40\%$). After this utilization



(a) *k*=1



(b) *k*=2



(c) *k*=3

Figure C.4: Bandwidth blocking ratio.

level, IM does not help to increase the achieved throughput. For high utilization levels, insufficient network resources become the main reason for blocking.

The performance increase obtained from IM, for lower traffic load, comes with a tradeoff. IM makes the algorithm use more wavelengths to accommodate the same amount of request. Figure C.5 gives the percentage of additional resources that are used for IM, over total resources used to accommodate the requests, for NSFNET.

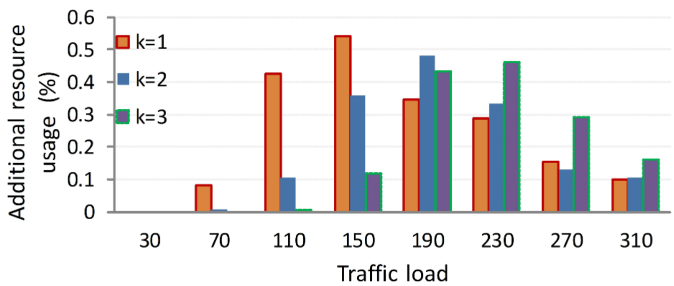


Figure C.5: Additional resource usage by IM.

The scheme that employs IM consumes up to 0.5% more network resources than the algorithm that does not employ IM. For high traffic loads, the performance of IM gets closer to the scheme that does not employ IM due to insufficient resources, thus the additional resource consumption ratio decreases.

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List of Publications and Patents:
▪ **Çukurtepe H.**, Kurnaz S., Şahin A.B. (2005). A required level for optical network business model: Integrated Neutral Topology Optimizer (INTO), *NEW TRENDS IN COMPUTER NETWORKS, Proc., ISCIS*, pp: 73-83.
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▪ **Çukurtepe H.**, Yayımlı A. and Mukherjee B. (2012). Inverse Multiplexing Gain Considering Physical Layer Impairments in Mixed Line Rate Networks, *in Proc., ISCC*, Cappadocia, Turkey.
▪ **Çukurtepe H.**, Tornatore M., Yayımlı A. and Mukherjee B. (2012). Impairment-Aware Lightpath Provisioning in Mixed Line Rate Networks, *IEEE ANTS'12*, Bangalore, India.
▪ **Çukurtepe H.**, Tornatore M., Yayımlı A. and Mukherjee B. (2013). Dynamic traffic

provisioning in mixed-line-rate networks with launch power determination (Invited talk) *ICTON*, Cartagena, Spain.

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- **Çukurtepe H.**, Tornatore M., Yayımlı A. and Mukherjee B. (2013). Provisioning of Dynamic Traffic in Mixed-Line-Rate Optical Networks With Launch Power Determination, *Accepted with minor revisions, Photonic Network Communications (PNET)*.