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# Connections Provisioning Strategies for Dynamic WDM Networks

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## Abstract

The size, complexity, and the amount of traffic generation of optical communication networks have dramatically increased over the last decades. Exciting technologies, namely, optical amplifiers, wavelength division multiplexing (WDM) and optical filters have been included in optical networks, in order to fulfill end users appetite for bandwidth. However, the users high bandwidth demand will further increase with time, as emerging on-demand bandwidth intensive applications are starting to dominate the networks. Applications such as interactive video, ultra-high definition TV, backup storage, grid computing, e-science, e-health to mention a few, are becoming increasingly attractive and important for the community. Given the high bandwidth requirements and strict service level specifications (SLSs) of such applications, WDM networks equipped with agile devices, such as reconfigurable optical add-drop multiplexers and tunable transceivers integrated with G-MPLS/ASON control-plane technology are advocated as a natural choice for their implementation. SLSs are metrics of a service level agreement (SLA), which is a contract between a customer and network operator. Apart from other candidate parameters, the set-up delay tolerance and connection holding-time have been defined as metrics of SLA.

This work addresses the network connections provisioning problem for the above mentioned demanding applications, by exploiting the time dimension of connections request. The problem is investigated for dynamic networks comprising ideal and non-ideal components in their physical layer, and for applications with differentiated set-up delay tolerance and quality of signal requirements. Various strategies for different scenarios are proposed, each strategy combining in a different way the concept of both set-up delay tolerance and connection holding-time awareness. The objectives of all these strategies are to enhance the network connections provisioning capability and to fulfill customers demand, by utilizing the network resources efficiently.

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# Contents

Ι	Introduction			1	
	Background and Overview				
	1	1 Introduction			
	2	Wide-area Networks Architecture			
	3	Optical Network Control			
	4	Optic	al Switching	8	
		4.1	Optical Circuit Switching	8	
		4.2	Optical Packet Switching	9	
		4.3	Optical Burst Switching	10	
	5	All-optical Routing			
		5.1	Physical Layer Impairments	12	
		5.2	Traffic Models	13	
		5.3	Control architecture for RWA	13	
		5.4	RWA algorithms for ideal physical layer	14	
		5.5	RWA algorithms for non-ideal physical layer	15	
	6 Quality of Service Issues in Optical Networks				
	7 Methodology for Performance Evaluation of Optical Network			19	
		7.1	Discrete Event Driven Simulation	19	
		7.2	Performance Metrics	20	
	8 Time Dimension Issues for Connections Provisioning			21	
		8.1	Advance Reservation	21	

	8.2	Holding-time	. 21
	8.3	Set-up Delay Tolerance	. 22
9	Traffic	c Re-optimization	. 24
10	Qualit	ty of Transmission	. 26
11	Concl	usion	. 28
12	Future	e Work	. 29
13	Contr	ibutions of the Thesis	. 30
14	Paper	s not Included in the Thesis	. 33

39

### **II** Included Papers

A Effect of Delay Tolerance in WDM Networks with Differentiated Services 41 1 43 $\mathbf{2}$ 453 Algorithms for service differentiated provisioning with delay 453.1453.2Priority Queue with Wavelength Reservation (PQ-WR) 463.3Priority Queue with Different Paths set (PQ-DP) . . . 464 46 5Conclusions 47**B** Reducing Blocking Probability in Dynamic WDM Networks Using Different Schemes  $\mathbf{53}$ 1 55 $\mathbf{2}$ Strategies for Enhancement of Network Blocking Performance 582.1Efficient RWA Algorithm 582.2Wavelength Conversion (WC) . . . . . . . . . . . . . 582.3Increasing the Network Resources . . . . . . . . . 58

		2.4	Re-routing Schemes	59	
		2.5	Set-up Delay Tolerance	59	
	3	Proble	m Statement and Notations	59	
	4	Queuing Strategy for Connection Provisioning with set-up De- lay Tolerance			
		4.1	Holding-time Aware (HTA) Strategy	60	
		4.2	Holding-time Unaware (HTUA) Strategy	61	
	5	Numerical Results			
		5.1	BP Comparison of Routing Strategies	62	
		5.2	BP Comparison of Different Strategies	63	
		5.3	Network Resources Utilization	64	
		5.4	Effect of $t_d$ on Network Connections Provisioning	65	
	6	Conclu	ision	65	
С	Red by I	ucing Rerout	Blocking Probability in Dynamic WDM Networks ing and set-up Delay Tolerance	69	
	1	Introd	uction	71	
	2	Related Work			
	3	Problem Statement and Notations			
	4	Proposed Strategies for Connection Provisioning			
		4.1	Algorithm Provisioning with set-up Delay Tolerance (PDT)	76	
		4.2	Algorithm MTV-FFWR	76	
		4.3	Algorithm MTV-SPA	76	
		4.4	Algorithm PDT with MTV-FFWR	76	
		4.5	Algorithm PDT with MTV-SPA	77	
	5	Numer	rical Results	77	
		5.1	Blocking Probability comparison of Proposed Strategies	79	
		5.2	Effect of Rerouting on set-up Delay Tolerance	81	
		5.3	Effect of Network size	82	
		5.4	Network Resources Utilization	83	
	6	Conclusion			

D	Impairment-Aware Dynamic Provisioning in WDM Networks					
	w 101	I Set-u	p Delay Tolerance and Holding-time Awareness	01		
	1	1 Introduction				
	2	Physic	cal-Layer Model	92		
		2.1	BER Estimation	93		
		2.2	Optical-Amplifier Model	94		
	3	Problem Statement and Notations				
	4	Strate	gy for Connection Provisioning with Delay Tolerance $\ .$	95		
		4.1	Holding-time Unaware (HTUA) Strategy	95		
		4.2	Holding-time Aware (HTA) Strategy	96		
	5	Numerical Results				
	6	Conclusion				
$\mathbf{E}$	Fair Scheduling of Dynamically Provisioned WDM Connec-tions with Differentiated Signal Quality10					
	1	Introd	uction	107		
	2	Impair	mpairment Aware Connection Provisioning			
	3	Proble	Problem Statement and Notations 11			
	4	Algori set-up	thms for Signal Quality Differentiated Provisioning with Delay Tolerance and Holding Time (Dif-DTHT)	113		
		4.1	Dif-DTHT with Backoff (Dif-DTHT-B)	113		
		4.2	Dif-DTHT with Resource Reservation (Dif-DTHT-RR)	114		
		4.3	Dif-DTHT by Mixing two Strategies (Dif-DTHT-Mix)	115		
	5	Nume	rical Results	115		
		5.1	Fairness and Comparison of Different QoT Classes in BP	117		
		5.2	Blocking Probability Comparison Under QoT Differ- entiation	118		
		5.3	Fairness Index for different strategies	119		
	6	Conch	ision	120		

### ABBREVIATIONS AND ACRONYMS

**AR** Advance Reservation

ASE Amplifier Spontaneous Emission

ASON Automatically Switched Optical Network

**BER** Bit Error Rate

**BP** Blocking Probability

**CD** Chromatic Dispersion

FEC Forward Error Correction

**FWM** Four Wave Mixing

GMPLS Generalized Multi-Protocol Label Switching

HTA Holding Time Aware

HTUA Holding Time Un-Aware

**IETF** Internet Engineering Task Force

**IR** Immediate Reservation

**ITU** International Telecommunication Union

**NDT** No Delay Tolerance

**NNI** Network-to-Network Interface

**OADM** Optical Add/Drop Multiplexer

**OBS** Optical Burst Switching

**OCS** Optical Circuit Switching

**OEO** Optical-Electrical-Optical

**OPS** Optical Packet Switching

**OSNR** Optical Signal-to-Noise Ratio

**O-VPN** Optical Virtual Private Network

- **OXC** Optical Cross Connect
- **PDL** Polarization Dependent Losses
- **PDT** Provision with Delay Tolerance
- **PLI** Physical Layer Impairments
- **PMD** Polarization Mode Dispersion
- $\mathbf{QoT}$  Quality of Transmission
- **RWA** Routing and Wavelength Assignment
- **SAPR** Shortest Available Path Routing
- **SBS** Stimulated Raman Scattering

SC Service Class

- **SLA** Service Level Agreement
- **SLS** Service Level Specification
- ${\bf SNR}$ Signal-to-Noise Ratio
- **SPM** Self Phase Modulation
- **TDM** Time Division Multiplexing
- **UHDTV** Ultra-high Definition TV
- **UNI** User-to-Network Interface
- VoD Video on Demand
- WA Wavelength Assignment
- WC Wavelength Conversion
- WCC Wavelength Continuity Constraint
- **WDM** Wavelength Division Multiplexing
- **XPM** Cross Phase Modulation

# Part I

# Introduction

## **Background and Overview**

## 1 Introduction

Optical networking has undergone tremendous change over the past three decades. Starting from unrepeated point-to-point transmission, the inventions of wavelength division multiplexing (WDM) and optical amplifiers have led to an explosion in system capacity, system reach, and network architecture. With advancements in the technology of optical components, the exploitation of optics has extended from WDM transmission to optical networking, which blends multiplexing, transmission, and optical switching. This has led to the building of the optical layer as a major part of the telecommunication transport infrastructure. The evolution in optical networking has focused on providing end user's demand for higher bandwidth in a cost-effective manner.

Today, the term optical network is used to denote networks that are not optical in the full meaning of the word. The currently deployed optical networks are mainly opaque, i.e., they utilize nodes (i.e., cross-connects) equipped with transponders. These transponders convert the input optical signals into electrical signals, and after processing by electronic switching matrices, convert these signals back into the optical domain for transmission. Similarly, other functional ingredients including multiplexing, add/drop and control are performed by electronics. Presently, optical connections are leased for long periods of time (e.g., weeks or months) requiring significant lead time to set-up and are configured manually. For survivability of connections in today's networks, ring topologies are often used, which utilize hardware related protocols for signaling the error status and initiating a switchover. Although this design is very beneficial from the aspect of switching time in case of failure event, its scalability and efficiency is very poor. Furthermore, various new applications such as video on demand (VoD), distribution of ultra-high definition TV (UHDTV), digital cinematic production, high definition interactive video conferencing, e-health, banking data backup storage, grid computing, e-science to mention a few, are expected to emerge over the next several years. These applications have the salient features of being user-controlled, bandwidth-intensive, and relatively short but known duration, thus demanding swift reconfigurable network devices of a type that are not deployed on current networks. With this future in mind, it can be seen that today's optical networks have the limitation of being inflexible, non-scalable, and expensive.

To overcome these shortcomings and fulfill future applications requirements, transparent optical (i.e., all-optical) WDM mesh networks with configurable optical layer and control plane have been proposed as the next generation optical networks. These networks will automatically self-configure in response to changing traffic demands, network faults or user requests. Moreover, the signal will remain in the optical domain (i.e., without optical-electricaloptical (OEO) conversion) all the way from source to destination, which enables these networks to be independent of protocol and coding formats, data rates, and modulation techniques. The feature of transparency offers several advantages. Firstly, transparency enables a network operator to provide a variety of different services using a single infrastructure. Secondly, if the protocols or data rates change in future, the equipment deployed in the network is still likely to be able to support the new protocols and/or data rates without requiring a complete overhaul of the entire network. Lastly, the data is carried from its source to destination in optical form, without undergoing an optical-to-electrical conversion along its entire path, which reduces the capital and operational costs of the networks as well as power consumption.

Despite the above mentioned benefits, there are some challenges associated with all-optical networks. Firstly, physical impairments such as chromatic dispersion, polarization mode dispersion (PMD), fiber nonlinearities, polarization-dependent degradations, WDM filter pass-band narrowing, component crosstalk, amplifier noise etc. accumulate over the physical path of the signal. The accumulations of these impairments have an impact on network design, either by adapting the size of WDM transparent domains or by incorporating impairments in the networking planning stage. Secondly, the rate of data transmitted over a single fiber in a transparent optical network will be in the range of terabits per second, and a short service disruption (due to any reason) will cause a large amount of data to be affected. Therefore, rapid fault identification and localization in these networks are very crucial. However, the identification and location of failures in transparent networks is very complex due to fault propagation, lack of digital information, and large processing time. A single fault can propagate all the way through an optical network and may generate several simultaneous alarms. This results in an increase in processing time to precisely locate the source of the fault. Besides the fault localization problem, transparent networks are vulnerable to sophisticated attacks that may not be possible in electronic networks. Thirdly, transparent networks do not allow wavelength conversion and therefore inflexible usage of wavelengths will lead to increased resources and network operational cost, thus negating the saving that may result from the elimination of optical-to-electrical conversion. Furthermore, the wavelength continuity constraint (i.e., same wavelength through the network) makes the sharing of backup resources difficult in survivable optical networks, and therefore the capacity requirements for protected services are significantly higher for such networks. Finally, for implementation of a scalable transparent optical network multi-vendor interoperable transport equipment is necessary, requiring international standardization efforts.

The potential benefits of transparent optical networks have attracted the research community to solve the above mentioned challenges. Several proposed solutions targeting different problem areas have been recommended by the researchers. Testbeds and demonstrators based on the proposed solutions have started to emerge, which will ultimately lead to their deployment in commercial networks. In the remainder of this chapter, a review of the various aspects of optical networks is presented. The contributions of the thesis along with brief descriptions of the included papers are listed in the end of the chapter.

## 2 Wide-area Networks Architecture

Wide-area WDM networks built on the concept of wavelength routing are envisioned to form the backbone for the all-optical network infrastructure. The wavelength routing utilizes the concept of circuit switching to provide optical connections called lightpaths, which traverse multiple fiber links and optical nodes. A lightpath is analogous to an electrical circuit, which must be requested, provisioned, and when it is no longer required, torn down. Fig. 1 illustrates a wavelength routing network consisting of two types of nodes:



Figure 1: A typical wavelength routed WDM network.

optical cross-connects (OXCs), which connect the fibers in the network, and edge nodes which provide the interface between non-optical end systems (e.g., IP routers, ATM switches, etc.) and the optical core. The edge nodes provide the terminating points (sources and destinations) for the lightpaths; the communication paths outside the optical part of the network may continue either in electrical or optical form depending on the access networks technology. Although, various architectures for optical access networks have been proposed in literature, in this work we focus only on wide-area WDM networks. Furthermore, with the emergence of bandwidth-intensive applications the concept of lightpath can be extended to end users, which assumes that an optical connection is provided all the way. The OXCs provide the switching and routing functions for supporting the lightpaths between edge nodes. An OXC takes in an optical signal at each of the wavelengths at an input port, and can switch it to a particular output port, independent of the other wavelengths. An OXC with N inputs and N outputs ports capable of handling W wavelengths per port can be thought of as W independent N x N switches. These switches have to be preceded by a wavelength demultiplexer and followed by a wavelength multiplexer to implement an OXC, as depicted in Fig. 2. Configuring the OXCs appropriately along the physical path, a lightpath may be established between any pair of edge nodes.



Figure 2: Optical cross-connect (OXC).

## **3** Optical Network Control

A substantial amount of operational cost in today's optical networks is due to their control and monitoring functions, which are manually implemented or depend on non-standard protocols. To improve these functionalities and create interoperability between network service providers the International Telecommunication Union telecommunications standardization sector (ITU-T) has standardized these functionalities under the name of ASON (i.e., automatically switched optical network). The concept of ASON is shown in Fig. 3 [1], which prescribes that the network has three layers: the transport plane, the control plane, and the management plane. The transport plane serves to transfer user information from source to destination in the optical domain along a lightpath. The control plane plays a central role and supports the functionalities of managing and allocating network resources, signaling the creation of a lightpath, providing network-to-network interfaces (NNI) to facilitate the exchange of relevant data with neighboring domains. Moreover, it also provides user to network interfaces (UNI) to enable automated bandwidth provisioning on demand. The centralized plane for management shown in the figure is only an example, and distributed management planes can also be applied in optical networks.

Similarly, the Internet engineering task force (IETF) has proposed generalized multi-protocol label switching (GMPLS), which is derived from multiprotocol label switching (MPLS). MPLS is basically a technique that allows



Figure 3: Control plane architecture [1].

traffic engineering by creating virtual switched circuits through an IP network. GMPLS extends this approach from packet switching to cover circuitoriented optical switching technologies such as time division multiplexing (TDM), and WDM. Apart from control plane architecture definitions, GM-PLS also defines a suite of protocols which can be used on transport network architectures based on either the ASON overlay network or its own GMPLS overlay [2].

## 4 Optical Switching

Optical switching is the cornerstone in the implementation of optical networking. Like switching in the electrical domain, there are two main methods of optical switching, namely, optical circuit switching (OCS) and optical packet switching (OPS). Also, in the recent years, optical burst switching (OBS) has been introduced as a compromise between OCS and OPS [3].

#### 4.1 Optical Circuit Switching

In optical circuit switching (OCS), switching is performed at the granularity of an optical lightpath (which may be wavelength, waveband, or entire fiber)



Figure 4: Lightpath configuration.

and is sometimes referred to as optical wavelength switching when the lightpath is based on a wavelength. Optical add/drop multiplexers (OADMs) and OXCs are utilized to configure the wavelengths as circuits across the network (Fig. 4). The current OCS technology is static reconfigurable, i.e., the OADMs and switches are reconfigured manually to set-up and reroute optical circuits in the time frame of hours to days. However, dynamic OCS which will be enabled by a new generation of fast configurable switching technologies (e.g., rapid tunable lasers and reconfigurable OADMs) has been proposed and analyzed as the switching paradigm for the future backbone networks [4, 5]. The dynamic OCS is well suited for dynamic demands, as it can provision bandwidth on-the-fly to emerging bandwidth-on-demand services.

This thesis work looks into the performance of dynamic WDM networks for the above mentioned emerging applications, thus the OCS at the granularity level of a wavelength is employed for connections provisioning.

#### 4.2 Optical Packet Switching

The "ultimate" optical network architecture proposed in literature is based on optical packet switching (OPS). An OPS is envisioned to provide the highest possible utilization of the optical core network. In OPS networks, data packets are switched and routed independently through the network entirely in the optical domain. An example of a basic optical packet-switched architecture is shown in Fig. 5. A node contains an optical switch fabric, which is capable of reconfiguration on a packet-by-packet basis. The switch fabric is reconfigured based on the information contained within the header of a packet. The header itself is typically processed electronically, and can either be carried in-band with the packet or carried out-of-band on a separate control channel. Since it takes some time for the header to be processed



Figure 5: An optical packet-switch architecture.

and for the switch to be reconfigured, the packet may have to be delayed by sending it through an optical delay line. Although research in OPS is in progress and testbeds and demonstrators have emerged, the technology is still far from being mature enough for commercial deployment. Some technical obstacles must be overcome which include the development of very high speed (nanosecond) switching fabrics, optical buffers, header recognition, and optical clock recovery.

### 4.3 Optical Burst Switching

Optical burst switching (OBS) is designed to bridge the gap between OCS and OPS in the core network. In OBS network, a data burst consisting of multiple IP packets is switched through the network all-optically. A control packet is transmitted ahead of the burst in order to configure the switches along the burst's route. The offset time (Fig. 6) allows for the control packet to be processed and the switch to be set-up before the burst arrives at the intermediate node; thus, no electronic or optical buffering is necessary at the intermediate nodes while the control packet is being processed. The control packet may also specify the duration of the burst in order to let the node know when it may configure its switch for the next arriving burst. By reserving resources only for a specified period of time rather than reserving resources for an indefinite period of time, the resources can be allocated in a more efficient manner and a higher degree of statistical multiplexing can be achieved. Thus, optical burst switching is able to overcome some of the limitations of static bandwidth allocation incurred by optical circuit switching. In addition, since data is transmitted in large bursts, optical burst switching



Figure 6: The use of offset time in OBS.

reduces the requirement of fast optical switches that is necessary for OPS. Although OBS appears to offer advantages over OCS and OPS, several issues need to be considered before OBS can be deployed in working networks. In particular, these issues include burst assembly, signaling schemes, contention resolution, burst scheduling, and quality of service.

## 5 All-optical Routing

To find a path and a free wavelength for a source-destination pair is one of the basic problems of all-optical routing. This is referred to in the literature as the Routing and Wavelength assignment (RWA) problem. The performance of a network depends not only on its physical resources (e.g., number of wavelengths per fiber, fiber links, etc.) but also on how it is controlled. The objective of an RWA algorithm is to achieve the best possible performance within the limits of the physical constraints. The RWA problem is known to be NP-complete, therefore it is usually addressed by a two-step approach to decrease its complexity. First finding a path from the source to the destination using a routing technique, and second, selecting a free wavelength on the chosen path using a wavelength assignment algorithm. The constraints of the RWA problem may include wavelength continuity, distinct wavelength, physical layer impairments (PLI), and traffic engineering considerations. The wavelength continuity constraint requires a connection to use the same wavelength along a lightpath. The wavelength continuity constraint can be relaxed by deploying wavelength converters in the network nodes. Distinct wavelength constraint imposes that all lightpaths traversing through the same link (fiber) must be allocated different wavelengths. The PLI constraint concerns how to select a wavelength and/or path that guarantee the required level of signal quality. The traffic engineering constraint aims to improve resource-usage efficiency and reduce connection blocking probability.

Initial studies on RWA problems relaxed the PLI constraint by considering a perfect transmission medium, and assumed all outcomes of the RWA algorithms as to be valid and feasible. However, the optical signals propagating through the fiber links and passive and/or active optical components encounter different sort of impairments that affect the signal intensity level, as well as its temporal, spectral and polarization properties. Thus the actual performance of the system may be unacceptable for some of the lightpaths. This thesis work studies RWA algorithms with only wavelength continuity constraint for papers A, B, and C. For papers D and E RWA algorithms with both wavelength continuity and PLI constraints are employed. A brief description of the classification of PLI, traffic models, network control architecture, and RWA algorithms for ideal and non-ideal physical layer are presented below.

#### 5.1 Physical Layer Impairments

The physical layer impairments encountered in optical networks can be classified into two categories: linear and non-linear impairments. Linear impairments affect each wavelength (optical channel) individually without creating interference or disturbance among the wavelengths, and are independent of the signal power. Nonlinear impairments, which are signal power dependent not only affect each wavelength, but also cause interference between them. The prominent linear impairments are: fiber attenuation, component insertion loss, amplifier spontaneous emission (ASE) noise, chromatic dispersion (CD), polarization mode dispersion (PMD), polarization dependent losses (PDL), crosstalk, and filter concatenation. Similarly, the important non-linear impairments can be summarized as self phase modulation (SPM), cross phase modulation (XPM), four wave mixing (FWM), stimulated brillouin scattering (SBS), and stimulated Raman scattering (SRS). A detailed description of all these impairments, their effect on optical feasibility, and techniques to mitigate their impact can be found in [6, 7]. Note that none of the existing studies has considered all the PLI in the RWA process. Each RWA algorithm incorporates only some specific PLI that depends on the assumed network scenario. The PLI considered in this work are: crosstalk, ASE noise, cross-saturation of erbium-doped finer amplifier (EDFA), receiver noise, fiber attenuation, and power loss in the optical components.

#### 5.2 Traffic Models

Two alternative traffic models are considered for all-optical networks: static traffic and dynamic traffic. Fig. 7 presents a conceptual view of a general static/dynamic traffic model. For static traffic, a set of connection requests is known in advance. The objective of the RWA problem for static traffic is to establish a set of light paths to accommodate all the connection requests while minimizing the number of wavelengths used in the network. The static RWA problem arises naturally in the design and capacity planning of an optical network (off-line RWA algorithms). For dynamic traffic, connection requests arrive to and depart from the network dynamically in a random manner. A lightpath is set-up when there is a connection request and is released when the data transfer is completed. The goal of the RWA problem for dynamic traffic is to route and assign wavelengths in such a way as to minimize the blocking probability of the network (online RWA algorithms). A connection is said to be blocked if there are not enough resources available to establish it. The dynamic RWA problem is encountered during the realtime network operational phase of the optical network. This work inquires the operational performance of optical networks, thus the dynamic traffic model is adopted for the RWA problem.



Figure 7: General traffic model.

## 5.3 Control architecture for RWA

Two architectures, centralized and distributed [8] control architecture have been proposed for all-optical networks. The centralized control architecture adopts a similar technique as used in a circuit-switched telephone network, whereas, the distributed control architecture resemble the approach implemented in packet data networks such as the Internet. In the centralized architecture, a controlling node monitors the network state and controls all resource allocations. When a connection request is received, an edge node sends a message to the controlling node. The controlling node executes the routing algorithm and the wavelength-assignment algorithm. Once a path and a free wavelength are selected, the controlling node will reserve resources (i.e., choose wavelength) on all nodes along that path. The distributed control architecture broadcasts information about the network state periodically, which enables each edge node to compute the path upon receipt of a connection request. Upon receiving a connection request, an edge node first executes the routing algorithm to compute a path and then it starts the wavelength-reservation protocol. The wavelength-assignment algorithm can be executed either by the destination node or by the source node to pick a free wavelength. The centralized control offers the benefit of full information about the network, and is employed for the RWA techniques in this work.

### 5.4 RWA algorithms for ideal physical layer

The routing algorithms can be divided into two categories: static and adaptive algorithms. In static routing algorithms (e.g., fixed routing [8], fixedalternative routing [8]), one or several paths are computed independently of the network state for each source-destination pair. Such algorithms are executed off-line and the computed paths are stored for later use, resulting in low latency during connection provisioning. However, these paths cannot respond to dynamic traffic conditions. Adaptive routing algorithms (e.g., shortest-path [8], shortest-cost-path [9], and least-congested-path [10]) are executed at the time a connection request arrives and require network nodes to exchange information regarding the network state. This exchange of information may increase the connection set-up time and computation cost, but in general, adaptive algorithms improve network performance.

Similarly, there are numerous wavelength-assignment algorithms reported in literature for both single and multifiber networks. For single-fiber networks, the Random algorithm [8] selects randomly one free wavelength from the unused wavelengths on the chosen path. The First-fit algorithm [8] picks the free wavelength with the smallest index. In the Most-used algorithm [8], the free wavelength which is used most often in the network is selected. In the Least-used algorithm [8], the free wavelength which is used least in the network is selected. All these algorithms that are first proposed for single fiber networks can also be extended to multifiber networks with and without modification [11]. However, other algorithms, e.g., Min-product [12], Least-loaded [13], Max-sum [14], and Relative-capacity-loss [15] have been proposed for multi-fiber networks to further improve the network performance.

Random and First-fit are the simplest algorithms in terms of computational complexity, and their running times are on the order of O(W), where Wdenotes the number of wavelengths in the network. Least-used and Mostused are more complex than Random and First-fit. For a single-fiber network with W wavelengths and L links, Least-used and Most-used will run in O(WL) [9] while for multi-fiber network with M fibers on each link, these algorithms will run in O(WLM) [9]. The computations in Min-product and Least-loaded will take O(KW), where K denotes the number of network nodes. Finally, Max-sum and Relative-capacity-loss are relatively expensive as for worse case scenario their computation cost will be  $O(WK^3)$  [9].

This study looks into single-fiber networks, and utilizes static routing and First-fit wavelength assignment algorithms due to their low computational time and network overhead. Moreover, adding wavelengths instead of deploying additional fiber is used to improve the network performance as it will add less to the computational time of the static routing and First-fit wavelength assignment algorithms.

#### 5.5 RWA algorithms for non-ideal physical layer

The incorporation of physical layer impairments (PLI) in transparent optical network planning and operation has recently received attention from the research community. The physical layer impairments (PLI) incurred due to the non-ideal network components reduce the number of candidate paths that can be selected for routing. Furthermore, a wavelength selection made for one lightpath affects and is influenced by the wavelength choice made for the other lightpaths, due to the PLI effect. For the incorporation of PLI in the RWA algorithms three approaches have been adopted in the literature: (a) Calculate the route and the wavelength in the traditional way, i.e., as described above for the ideal physical layer, and verify the feasibility of selected lightpath by considering the PLI; (b) Incorporate the PLI values while selecting the route and/or wavelength for a connection request: (c) Consider the PLI values in the routing and/or wavelength assignment decision and finally verify the signal quality of the candidate lightpath. These approaches and their various combinations are depicted in Fig. 8 (adapted from [16]).



Figure 8: Various PLI-RWA approaches [16].

In the A-1 case the route and wavelength are computed without considering the PLI constraints, but the wavelength assignment (WA) decision can be modified after the verification phase. A-2 calculates the route without taking into account the PLI, but there is an option of recomputing the route if the PLI constraints are not fulfilled by the candidate route(s). Similarly, A-3 computes the route and wavelength (either in one step or two) using traditional schemes and then checks the PLI constraints in order to possibly change the RWA decision. The approaches in group B address the RWA problem by incorporating the physical layer information: in the B-1 case the route is computed using PLI constraints: in the B-2 case these constraints are considered in the wavelength assignment process; lastly in the B-3 case the PLI constraints are taken into account in both route and wavelength selection. Some of the works that adopt the last approach use the physical layer information as weights associated with the links, in order to calculate the minimum cost lightpath. Approach C is the combination of the last two approaches. The PLI constraints are taken into account in the routing (C-1), or in the wavelength assignment (C-2) or in both (C-3); but the PLI constraints are finally verified that enable the re-attempt process in the lightpath selection phase.

Similarly, there are two procedures for accounting for the interference among the lightpaths while addressing the PLI-RWA problem. The first technique chooses a lightpath for a new connection request that has acceptable transmission quality under a worst case interference assumption, ensuring that the selected lightpath will not become infeasible due to the possible establishment of future interfering connections. The second technique considers the current network state and the actual interference among the lightpaths. This technique performs a cross layer optimization between the network and physical layers, and checks whether or not the establishment of the new lightpath will make any already established connection infeasible. The former approach is less complex and calculates a quick and stable lightpath at the expense of reducing the candidate path space available for routing. The latter approach performs better by exploring a larger path space at the cost of adding complexity introduced by the cross-layer optimization.

This thesis work picks the C-2 approach for the part that takes into account the PLI, and employs the current network state to calculate the actual interference among the lightpaths.

## 6 Quality of Service Issues in Optical Networks

The next generation optical networks will provide a unified platform for existing and new emerging network services. A key feature of next generation optical networks is the capability not only to fulfill the functional requirements of these services, but also to offer differentiated services to accommodate the different requirements of the customers. Fig. 9 (adapted from [17]) shows the different types of services that can be envisioned in future optical networks, along the following dimensions: the degree of variability of the bandwidth, the degree of automation of the connection establishment,



Figure 9: Classification of services [17].

and the degree of customer visibility of the resources that are allocated to him. The leased-line type of service has fixed bandwidth and can tolerate a low level of connection automation. For the preprovisioned bandwidth case, bandwidth variation is supposed to exist. Bandwidth on demand service is more constraining for the operator as it requires real-time provisioning of bandwidth without previous knowledge of demand variations. A high level of connection automation is then mandatory. Finally, the optical virtual private network (O-VPN) [18] is a multipoint-to-multipoint service where the customer has some visibility of the resources allocated to him and possibly the opportunity to partially directly manage them.

Service differentiation is a valuable opportunity for operators to increase their income from their infrastructure, by selling high added-value services. A service level agreement (SLA) is a formal contract between a service provider and a customer that contains detailed technical specifications called service level specifications (SLSs). A SLS is a set of parameters and their values that together define the service offered to a customer. There are no standards defined for the contents of an SLA, however Fig. 10 depicts some parameters that can be included in an optical SLA as proposed in [17]. In addition to these parameters, different classes of services, namely, premium, gold, silver, and bronze with different specifications have also been proposed in [17]. All these metrics of SLA will not only assist the customers to select an appropriate service class in compliance with their requirements, but will also benefit the service providers by managing their network resources



Figure 10: Parameters for optical SLA [17].

efficiently.

This thesis work treats service differentiation issues in optical networks, and classify the connection requests into different service classes based on their set-up delay tolerance[19] and signal quality of transmission requirements (papers A, E). The proposed strategies for service differentiation are particularly tailored to facilitate the provisioning of the most stringent service class so as to balance the success rate among the different classes. Furthermore, the strategies make use of the connections holding-time awareness[20] for enhancing their performance.

## 7 Methodology for Performance Evaluation of Optical Networks

Experimental set-ups are often used by the research community for validation of hypotheses and the required outputs or results from the experimental set-ups are analyzed to answer the aims or hypotheses. The selection of experimental set-ups depends on the research discipline. In the field of optical networking, discrete event driven simulation is usually used by researchers as a tool for evaluation of their proposed solutions. A brief description of discrete event driven simulation and the performance metrics for optical networks are presented below.

#### 7.1 Discrete Event Driven Simulation

Simulation is the imitation of the operation of a real-world process or system over time. In optical networks, most of the time it is difficult to develop an analytical model for estimating system performance, due to complicated system structures and complex traffic pattern. Thus, discrete event driven simulation can be a feasible and efficient solution to assess network and system performance. In discrete event driven simulation a set of state variables collect all the information needed to define what is happening within a system. The system changes only at those discrete points in time at which events occur. The system state is updated at each event, along with occupying or freeing of system resources that might occur at that time.

In the framework of this thesis, a simulation tool based on discrete events has been developed for evaluation of dynamic scheduling algorithms. The developed simulator is specifically tailored to meet the requirements of each scenario under consideration. The arrival or departure of connection request acts as an event for the simulator, while the wavelengths on each fiber link of the network are considered as system resources. The system statistics, i.e., the parameters of interest (e.g., connections blocking percentage and resource utilization) are calculated from the system state variables. The simulation terminates after processing adequate number of events, while the number of runs of each simulation is set so as to achieve a desired confidence level.

### 7.2 Performance Metrics

The conventional method for evaluating the performance of the proposed RWA algorithms in the literature is the percentage of blocked connection requests versus the traffic load for the dynamic traffic scenario. The same metric along with calculating the amount of necessary resources (fibers per link, wavelengths, etc.) required for a given network blocking is used in the static traffic scenario. As mentioned above the RWA algorithms with static traffic are utilized in the design phase, hence the objective is to minimize the number of essential wavelengths or the required regenerators in case of translucent networks. In contrast, RWA algorithms with dynamic traffic are employed in the operational phase with the aim to route the maximum number of connection requests, and therefore the percentage of blocked requests (or blocking probability) is used in order to compare the performance of different algorithms.

Some studies report different performance metrics. For example, the authors in [21] investigate their proposed strategies for the resource utilization (in terms of average and standard deviation of link, transmitter, receiver, and interface utilization) along with network blocking probability. Similarly, [22] finds the results for the regenerator usage and the number of essential transponders. Some authors evaluate their strategies for the computational time, for instance the work reported in [23, 24]. Fairness and the impact of impairments accumulation on the maximum transmission distance are reported in [25, 26] and [27], respectively.

This study makes use of various metrics, namely, percentage of blocked connections, network resource utilization and fairness, for the performance evaluation of the proposed strategies. All the scenarios investigated in this thesis are dynamic, thus the percentage of blocked connections is a common metric for these scenarios. A fairness value denoted Jain's fairness index [28] is used to evaluate the performance of the proposed strategies in paper E.

## 8 Time Dimension Issues for Connections Provisioning

Network connections provisioning and consequently network blocking performance can be improved significantly by exploiting the temporal related metrics of SLA, such as connection set-up time and connection holdingtime. Similarly, reserving network resources prior to utilizing them can also enhance network connections provisioning.

#### 8.1 Advance Reservation

The RWA models explained above only consider the so-called "immediate reservation" (IR) requests, which are made just at the time when the network resources (i.e., wavelength) are actually required. A connection request will be blocked if the network resources are not available at the time when they are needed. IR benefits those applications that are delay-sensitive, for instance online gaming and video streaming. However, some applications, for instance banking backup data, grid computing, and e-science can be delay-tolerant as long as the network resources are provisioned before a deadline. For such applications, an advance reservation [29] (AR) mechanism can greatly enhance their provisioning probability. Unlike immediate reservation, an AR request specifies a start time that is in the future and a specific holding-time. The time interval between reservation and utilization of the network resources is denoted as the book-ahead time. AR not only provides guaranteed services to network users, but also allows network operators to plan their resources allocations efficiently, and consequently increases their revenue. Several models for AR based on whether the starting time and/or holding-time are specified or not, are described in [29]. All these models have been thoroughly investigated by the research community, and a comprehensive literature survey on AR RWA can be found in [30]. The book-ahead time enables the connection requests [30] to seek free network resources, however it may result in resources fragmentation unless flexibility in reservation time window [31] or re-optimization techniques [32, 33] are employed.

#### 8.2 Holding-time

Holding-time describes the duration for which a connection remains active and occupies the network resources. As mentioned above, new applications are emerging with requirements of large bandwidth over relatively short and predictable periods of time, for instance video distribution of important sport or social events. It is expected that the holding-time of connection requests can be known in advance, as it is considered to be a metric of the SLA between the network operator and its customers [34]. The prior knowledge of connections holding-time has been exploited for different dynamic network scenarios, for instance efficient utilization of lightpath capacity and bandwidth allocation for the traffic grooming problem [20], enhancement of backup resource sharability in survivable networks [35] and for efficient load balancing [36].

This work also exploits the holding-time awareness by combining it with set-up delay tolerance, in the context of resource optimization for dynamic lightpath provisioning. The knowledge of connections holding-time can be utilized to retrieve the information about the departing connections, and that information can be used for efficient provisioning of waiting connection requests. The performance improvement due to the combination of these two metrics is investigated with and without the assumption of an ideal optical medium.

#### 8.3 Set-up Delay Tolerance

Advance reservation (AR) enables network users to ensure the availability of resources prior to when they are required. For immediate reservation (IR) connection requests, which require immediate provisioning and allocation of resources it may happen the resources are not free at the time when the request arrives. However, they might be free shortly thereafter when some active connections depart from the network. For IR connection requests, set-up delay tolerance[19] has been proposed for improving the connections provisioning. Set-up delay tolerance describes customer patience, i.e., the maximum duration a customer is willing to wait until the connection is setup. Set-up delay tolerance is a special case of AR tailored to facilitate the provisioning of delay-sensitive connection requests. The waiting time in the delay tolerance case is expected to be a fraction of the connection request holding-time, and the connection request is provisioned immediately after the required resources become free within its waiting time, which leads to efficient utilization of resources.

Paper A looks into a scenario where connection requests are categorized into three service classes (i.e., SC-I, SC-II, and SC-III) based on the set-up delay tolerance. Among these SCs, SC-III has high set-up delay tolerance which is followed by SC-II, and then by SC-I. It is observed that SC-II and SC-III performance is improved compared to the basic approach, i.e., provisioning with no delay tolerance (NDT) as shown in Fig. 11. However, the blocking performance of SC-I, which requires stringent set-up delay tolerance, deteriorates compared to NDT. High set-up delay tolerance of SC-II and SC-III enabled these SCs to occupy the network resources, which consequently reduce the chance for SC-I connection requests to get connected. Paper A proposes some scheduling algorithms, which are able to significantly reduce the blocking probability of each service class individually together with the total network blocking probability.

Similarly, paper B compares the gain in network performance due to exploiting set-up delay tolerance combined with holding-time awareness with other available methodologies for improvement of network performance. The aim is to evaluate these different approaches for a wide range of network loads in order to find the relative merits of the methodologies. This information can be beneficial for selecting a good strategy to design a network with a specific performance requirement. Apart from comparing these different approaches, paper B also proposes a novel strategy which utilizes holding-time awareness more efficiently than the strategy proposed in [19]. Fig. 12 shows the normalized (with respect to NDT with wavelength continuity constraint (WCC)) blocking probability of different strategies for three different traffic load cases. The average gain of the proposed novel strategy (PDT-HTA) over the one employed in [19] (i.e., PDT-HTA-WNR) is 6%, while its aver-



Figure 11: Blocking probability for 30 nodes European core network.



Figure 12: Normalized blocking probability for 14 nodes NSF network.

age gain over the holding-time unaware strategy (i.e., PDT-HTUA) is 9%. Moreover, at low and medium loads the strategy provisioned with set-up delay tolerance combined with holding-time awareness (i.e., PDT-HTA) shows better result compared to other strategies.

Papers A and B study networks with ideal optical medium, i.e., no physical layer impairments. However, paper D looks into networks with non-ideal components in its physical layer and investigates the reduction in blocking probability (BP) by utilizing set-up delay tolerance and holding-time awareness. In physical layer impaired networks, connection requests can be blocked for two reasons. Either there is a shortage of wavelength resources or the quality of the optical signal fails to achieve a required quality level regardless of the availability of wavelength resources.

For such networks, the BP can be improved significantly by employing the set-up delay tolerance and holding-time awareness approach. Fig. 13 shows that the network BP reduces on average 38% for the strategy that employs only set-up delay tolerance (PDT-HTUA) and 48% when both set-up delay tolerance and holding-time awareness (PDT-HTA) are utilized.

## 9 Traffic Re-optimization

In dynamic WDM networks connection arrivals and departures are stochastic in nature and connections provisioning is accomplished via online RWA



Figure 13: Blocking probability for 14 nodes NSF network scaled down by a factor of 10.

algorithms. Hence, it is likely that after some time, some of the already provisioned connections may become sub-optimal with respect to the current state of the network. To lower the risk of blocking of future connection requests due to inefficient utilization of network resources, it is desirable to seek a new RWA solution for all (or a subset) of the active connections. Migrating traffic from their current existing connection configuration to the new one is referred to as traffic migration or traffic configuration. Another term, call rerouting is also used in the literature for the action of altering the physical path and/or wavelength of an established connection. The rerouting can be divided in two schemes, i.e., passive and intentional [37]. Passive schemes reroute some of the active connections in order to provision a new request in the network, which will be blocked otherwise. On the other hand intentional schemes try to keep the network in an optimal state, by rerouting the active connections dynamically to a more appropriate physical path and wavelength either at some predefined time instances or at periodic intervals.

Paper C proposes two different heuristic passive rerouting strategies for dynamic WDM networks with ideal optical medium. Whenever a new connection request fails to get connected, one of the strategies (MTV-FFWR) retunes (i.e., wavelength reassigns) all those active connections to new wavelengths whose paths overlap with the k-shortest paths of that new arrival request. The other strategy (MTV-SPA) reroutes all those active connections to new paths and/or wavelengths whose current paths overlap with the



Figure 14: Normalized blocking probability for 14 nodes NSF network.

k-shortest paths of that new arrival request. The objective is to minimize the network BP and utilize network resources more efficiently. Therefore, apart from accommodating the new request, the strategies re-optimize a subset of existing active connections configuration so that the blocking of the future connection requests may be reduced. The strategies are evaluated both with, and without set-up delay tolerance. The BP is normalized to that of the shortest available path routing (SAPR) BP, which is used here for benchmark purpose. Fig. 14 shows that the proposed strategies reduce network BP significantly even without combining with set-up delay tolerance. There is a further drastic reduction in BP when the strategies are combined with set-up delay tolerance.

## 10 Quality of Transmission

The quality of transmission (QoT) of the provisioned connections (lightpaths) can be measured in terms of bit error rate (BER) or equivalently, in terms of Q-factor [6]. The BER of an optical path depends on the span of the physical links and the number and type of links/nodes traversed by the optical signal. At low line rates, i.e., 2.5 Gb/s and 10 Gb/s BER measurements take considerable amount of time to achieve statistically valid results [7]. However, the Q-factor which measures the quality of an analog transmission signal in terms of its signal-to-noise ratio (SNR) can determine error ratio faster than the BER test. A high Q-factor means better



Figure 15: Blocking probability for 14 nodes NSF network scaled down by a factor of 10.

optical signal-to-noise ratio (OSNR), and thus lower probability of bit errors. The QoT requirements varies with applications, for instance sensitive backup data (e.g., financial transactions and banking) demands a BER value of  $10^{-15}$  or equivalently a Q-factor equal to 9, compared to Gigabit Ethernet which requires these values to be  $10^{-12}$  and 8, respectively [7]. Forward error correction (FEC) reduce the bit errors, however applications with tight latency requirements (e.g., interactive communication and streaming data) have less room for error correction and consequently require high QoT [38].

When exploring a scenario where connection requests are classified in different service classes based on their QoT requirements, the provisioning success rate might become unbalanced towards those connection requests with less stringent requirements. I.e., not all the connection requests are treated fairly. To examine such a situation, paper E considers the differentiation of service classes in terms of signal quality, where each service class, namely, SC-I, SC-II, and SC-III, requires a different QoT level, i.e., SC-I demands higher QoT followed by SC-II, and then by SC-III. Fig. 15 shows the normalized BP for two strategies that exploit set-up delay tolerance and holding-time awareness with advance reservation of network resources (DTHT-RR) and without reservation (DTHT). These strategies are compared with a basic approach, i.e., the impairment-aware provisioning with no delay tolerance (NDT). The BP is normalized using the SC-I BP value for NDT. The BP of each class and the total network BP are reduced significantly when a set-up delay tolerance and a holding-time aware approach is used. However, the BP of SC-I is 48% higher than SC-II for NDT, and this difference becomes more substantial when the DTHT and DTHT-RR approaches are used, i.e., 50% and 53%, respectively. In order to balance the provisioning success rate among all service classes and to improve the fairness of the network, paper E proposes three fair scheduling algorithms in a dynamic traffic scenario. Each one combines in a different way the concept of both set-up delay tolerance and connection holding-time awareness, and are able to guarantee a fair treatment reaching up to 99% in terms of Jain's fairness index, considering the per-class success rate.

## 11 Conclusion

The future optical networks are envisioned to be highly dynamic and user controlled. Such networks will provide a platform for the new emerging applications that require huge bandwidth for comparatively short duration. Bandwidth services will be seen as a commodity, thus multiple network operators will compete for customers by offering comparable prices. Service level agreements (SLA) between customer and network operator will specify in measurable terms the service that the customer should receive.

SLA metrics such as set-up delay tolerance and connection holding-time awareness can enable the network operators to improve the overall network performance in terms of network blocking. The gain in network performance by exploiting these metrics depends on network parameters such as network size, network nodal degree, and network load. At low and medium loads, blocking in the network occurs due to capacity exhaustion at some links. Thus employing set-up delay tolerance and holding-time awareness at these loads show better results compared to deploying wavelength converters at network nodes or supplying extra wavelengths to the network. Similarly, for physical layer impaired networks where connection request is blocked not only due to the resource unavailability but also due to reduced signal quality, exploring the two SLA metrics for such networks exhibits drastic improvement in network blocking. For impatient connection requests, i.e., requests with smaller set-up delay tolerance, the provisioning chance can be improved by rerouting some of the active connections.

However, for scenarios where network connection requests have different setup delay tolerance or signal quality requirements (i.e., belong to different service classes), the blocking performance of some service classes will not be as good as the overall network blocking ratio. The service class that requires relatively low signal quality or high set-up delay tolerance has more chance to be successfully provisioned when compared to the other (more stringent) classes. For these scenarios it is important to develop some strategies that improve the network fairness by keeping a balance among the success rate of the different service classes.

To conclude, several different aspects related to improving the performance of dynamic WDM networks have been presented. Fig. 16 highlights the various issues that are investigated in this thesis work.



Figure 16: Summary of the various issues studied in this work.

## 12 Future Work

Several areas are identified for the extension of this thesis work. For instance, in real networks immediate and advance reservation connection requests will co-exist. The work so far on this topic, i.e., mixed traffic has considered the known holding-time assumption only for advance reservation requests, which always get priority over immediate reservation requests in network resources. It will be useful to explore holding-time awareness and set-up delay tolerance for immediate reservation requests in a mixed traffic scenario. Furthermore, it will be interesting to investigate the case where immediate reservation requests are treated as urgent and require higher priority. Similarly, the admission control mechanisms to solve the conflict in using the network resources among these traffic demands need to be examined.

The physical layer impairments constraint has not yet been considered in the RWA strategies for advance reservation problem, which imposes the need to look into this issue. Finally, the service differentiation issue can be extended by classifying service classes with different set-up delay tolerance and QoT requirements.

## 13 Contributions of the Thesis

In this thesis we focus on wavelength-switched wide-area WDM networks with dynamic traffic and centralized RWA decision. We analyze the improvement in network performance when the SLA parameters are fully exploited for lightpaths provisioning, and for scenarios where connection requests belong to the same and different service classes.

Brief summaries of the papers included in this thesis are as follows:

#### Paper A: Effect of Delay Tolerance in WDM Networks with Differentiated Services

Authored by A. Muhammad, C. Cavder, L. Wosinska, and R. Forchheimer.

Published in the proceedings of OFC/NFOEC, 2011.

**Abstract:** We study a dynamic WDM network supporting different service classes (SC) containing applications having similar set-up delay tolerance. By utilizing delay tolerance we propose scheduling strategies able to significantly reduce blocking probability of each SC.

**Contribution:** The contributions consist of the refinement of the initial idea through experiments, implementation of algorithms and drafting of the text.

### Paper B: Reducing Blocking Probability in Dynamic WDM Networks Using Different Schemes

Authored by A. Muhammad, and R. Forchheimer.

Published in the proceedings of IEEE NoF, 2011.

Abstract: We compare the performance of a dynamic WDM network for different blocking probability (BP) improvement strategies. First we analyze a strategy which efficiently utilizes two Service Level Agreement (SLA) metrics, i.e., holding-time combined with set-up delay tolerance, for connection provisioning. We investigate its performance improvement compared to the earlier proposed scheme and with the strategy which exploits only the set-up delay tolerance for connection provisioning. Secondly, we evaluate the performance of the various approaches for network blocking reduction over a wide range of network loads. Our aim is to obtain insight information that can be useful for selection of an optimal strategy for designing a network, with specific network parameters and performance requirements.

**Contribution:** The contributions consist of refinement of the initial idea through experiments, implementation of algorithms and writing the text.

#### Paper C: Reducing Blocking Probability in Dynamic WDM Networks by Rerouting and set-up Delay Tolerance

Authored by A. Muhammad, and R. Forchheimer.

Published in the proceedings of IEEE ICON, 2011.

**Abstract:** With the emergence of bandwidth intensive applications new methodologies need to be developed for improvement of network blocking performance, without supplying extra resources in dynamic wavelengthdivision-multiplexing (WDM) networks. Rerouting is one among the viable and cost-effective solutions to reduce the blocking probability (BP) of optical WDM networks. Similarly, set-up delay tolerance, a metric of service level agreement (SLA) has been earlier exploited in for improvement in network BP. In this paper, we study the rerouting in dynamic WDM network and analyze two different lightpath rerouting strategies. Moreover, we investigate further improvement in network BP by exploiting these rerouting techniques for network provisioned with set-up delay tolerance. Through extensive simulation studies, we confirm that the rerouting strategies decrease the BP substantially for network provisioned with set-up delay tolerance, even for smaller set-up delay tolerance value, i.e., when the connection requests are impatient to wait for provisioning in the network. However, it also reduce BP significantly even when the network is not provisioned with set-up delay tolerance.

**Contribution:** The contributions are the initial idea, implementing the algorithm, performing the experiments and writing the text.

#### Paper D: Impairment-Aware Dynamic Provisioning in WDM Networks with set-up Delay Tolerance and Holding-time Awareness

Authored by A. Muhammad, R. Forchheimer, and L. Wosinska

Published in the proceedings of IEEE ICON, 2011.

**Abstract:** We study a dynamic WDM network with non-ideal components in the physical layer which uses an impairment-aware routing and wavelength (RWA) algorithm for connection provisioning. We investigate the reduction in blocking probability (BP) by utilizing service Level Agreement (SLA) metric, i.e., set-up delay tolerance during connection provisioning. Furthermore, we explore the improvement in the network performance by efficiently utilizing the knowledge of the connections holding-time, another metric of SLA. Keeping in mind that BP reduction can be obtained by set-up delay tolerance our focus is to investigate how set-up delay tolerance combined with holding-time awareness can improve BP performance caused by physical impairment. Our simulation results confirm that significant improvement can be achieved by holding-time aware connection provisioning compared to the unaware holding-time case. Moreover as expected, set-up delay tolerance can reduce BP even without knowledge of connections holding-time.

**Contribution:** The contributions consist of refinement of the initial idea through experiments, implementation of algorithms and drafting of the text.

#### Paper E: Fair Scheduling of Dynamically Provisioned WDM Connections with Differentiated Signal Quality

Authored by A. Muhammad, C. Cicek, and P. Monti

Published in the proceedings of IEEE ONDM, 2012.

**Abstract:** Emerging on-demand applications (e.g., interactive video, ultrahigh definition TV, backup storage and grid computing) are gaining momentum and are becoming increasingly important. Given the high bandwidth required by these applications, Wavelength Division Multiplexing (WDM) networks are seen as the natural choice for their transport technology. Among the various on-line strategies proposed to provision such services, the ones exploiting the connection holding-time knowledge and the flexibility provided by set-up delay tolerance showed a good potential in improving the overall network blocking performance. However, in a scenario where connection requests are grouped in different service classes, the provisioning success rate might be unbalanced towards those connection requests with less stringent requirements, i.e., not all connection requests are treated in a fair way.

This paper addresses the problem of how to guarantee the signal quality and fair provisioning of different service classes, where each class corresponds to a specified target of quality of transmission (QoT). With this objective in mind three fair scheduling algorithms are proposed, each one combining in a different way the concept of both set-up delay tolerance and connection holding-time awareness under dynamic traffic scenario. Proposed solutions are specifically tailored to facilitate the provisioning of the most stringent service class so as to balance the success rate among the different classes. Simulation results confirm that the proposed approaches are able to guarantee a fair treatment reaching up to 99 % in terms of Jain's fairness index, considering per-class success ratio, without compromising the improvements in terms of overall network blocking probability.

**Contribution:** The contributions are refinement of initial idea through experiments, implementation of algorithms and writing some part of the text.

## 14 Papers not Included in the Thesis

The following papers contain work done by the author but are not included in this thesis.

1. A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, "Energy-Efficient WDM Network Planning with Protection Resources in Sleep Mode" in *proc. of IEEE GLOBECOM 2010*.

2. P. Monti, A. Muhammad, I. Cerutti, C. Cavdar, L. Wosinska, P. Castoldi, A. Tzanakaki, "Energy-Efficient Lightpath Provisioning in a Static WDM Network with Dedicated Path Protection" in *proc. of IEEE ICTON 2011*.

. Background and Overview

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