Universitat Politècnica de Catalunya
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"Physical Impairments Aware Planning and Operation of Transparent Optical Networks"

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Dedication

To my precious wife, ***Mozhgan***
and to my cherished son, ***Parsa***
for their love and patience

Acknowledgements

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Athens, 7 June 2010
Siamak Azodolmolky

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1 - www.diconet.eu
2 - www.ict-bone.eu

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List of Acronyms

ASE	Amplifier Spontaneous Emission
ASON	Automatically Switched Optical Networks
BER	Bit Error Rate
CAPEX	Capital Expenditure
CD	Chromatic Dispersion
DWDM	Dense Wavelength Division Multiplexing
FC	Filter Concatenation
FWM	Four Wave Mixing
GMPLS	Generalized Multiprotocol Label Switching
IA-RWA	Impairment Aware Routing and Wavelength Assignment
IETF	Internet Engineering Task Force
ILP	Integer Linear Programming
ISI	Inter Symbol Interference
LP	Linear Programming
MCP	Multi-Constraint Path
NMS	Network Management System
NMS	Network Management System
NPOT	Network Planning and Operation Tool
OADM	Optical Add Drop Multiplexer
OAM	Operation, Administration, and Maintenance
OEO	Optical Electronic Optical
OIF	Optical Internetworking Forum
OPEX	Operation Expenditure
OPM	Optical Performance Monitoring
OSNR	Optical Signal to Noise Ratio
OSPF-TE	Open Shortest Path First with Traffic Engineering
OTN	Optical Transport Network
OXC	Optical Cross Connect
PCE	Path Computation Element
PLD	Permanent Lightpath Demand
PLI	Physical Layer Impairments
PMD	Polarization Mode Dispersion
QoT	Quality of Transmission
ROADM	Reconfigurable Add Drop Multiplexer
RWA	Routing and Wavelength Assignment
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
SPM	Self Phase Modulation
TED	Traffic Engineering Database
UNI	User Network Interface
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation
XT	Crosstalk

Summary

Core optical networks using reconfigurable optical switches and tuneable lasers appear to be on the road towards widespread deployment and could evolve to all-optical mesh networks in the coming future. No matter which architecture is considered, the main goal of these architectures is to provide the required infrastructure for end-to-end connection establishment in a cost effective manner. Efficient planning and operation of transparent optical network introduces interesting challenges, which are addressed in this study.

When selecting a lightpath (route and wavelength), a routing and wavelength assignment (RWA) algorithm for a transparent or translucent network has to take into account the physical layer impairments as well as the wavelength availability. With static traffic (i.e., network planning), the entire set of connection requests is known in advance, and the static (off-line) RWA problem of setting up these connection requests is named the offline impairment aware RWA (IA-RWA) problem. There are quite few proposals that address the resilience and protection issues in the IA-RWA algorithms for network planning. In static (off-line) case, there is enough time between the planning and provisioning (i.e., actual lightpath establishment) processes such that any additional equipment required by the plan can be deployed. In this context, the main goal is to accommodate the whole demand set.

In a dynamic traffic scenario, the connections are requested in some random fashion, and the lightpaths have to be set up as needed. In dynamic traffic scenario, there is little time between planning and provisioning, and demands are generally processed one at a time. It is assumed that the demand set must be accommodated using whatever equipment is already deployed in the network. Thus, the IA-RWA proposal must take into account any constraints posed by the current state of the network, which may force a demand to be routed over a sub-optimal path. One big challenge for IA-RWA algorithms is the Quality of Transmission (QoT)-awareness, in the sense that they must ensure (during admission control) that all lightpaths in the network meet a QoT constraint (e.g., BER) without disrupting previously established lightpaths.

In addition to simulation studies, experimental and some analytical models are available to evaluate the performance of the proposed algorithms. None of the surveyed works considers the inaccuracy of the physical impairment information (analytically computed or measured) into their IA-RWA algorithms. The proposed adaptive IA-RWA algorithms simply change their decisions assuming that the physical information are completely accurate.

In the first chapter, the evolution of optical networking, the hierarchical model and layered models, along with the evolution of configurable optical networks and planning and operation of them is compiled.

In the second chapter of this Ph.D. dissertation a comprehensive study on current proposals on impairment aware optical networking is compiled. The general approach to address the IA-RWA problem can be divided in two main categories. The first trend utilizes traditional RWA algorithms and after selecting the lightpath the physical constraints are verified. The second approach is to use some metrics, which are related to the physical layer impairments as cost of the links in order to compute the shortest path(s). The physical impairments and IA-RWA algorithms can be incorporated in control planes using various integration schemes.

Evaluating the performance of the physical layer and the impact of physical layer impairments on the optical signals plays an important role. In the third chapter (Chapter 3) the physical layer impairments, their classification and impacts, the proposed models and also the QoT estimator, which is utilized in the contributed algorithms are presented. In fact the QoT estimator is one of the key building blocks for impairment aware planning and operation of optical networks.

The contributed impairment aware network planning algorithm, which is named ***offline Rahyab,*** is presented in Chapter 4. The contribution of *Offline Rahyab* is four-fold. First, the offline Rahyab by design is a novel IA-RWA that natively accounts for dedicated path protection; second, a selected heuristic algorithm from the literature to better include QoT related impairments and to consider the dedicated path protection is enhanced and its performance with *offline Rahyab* is compared. Third, an ILP-based RWA formulation, from the state-of-the-art algorithms at the time of impairment aware planning study is enhanced, to include QoT requirements and also to incorporate protected demands and their performances under similar performance evaluation framework are compared. The novel heuristic algorithm performs better than the selected algorithms under the same assumptions. Finally, a potential usage of *offline Rahyab* as a re-routing strategy is demonstrated. The *offline Rahyab* algorithm solves the offline traffic problem in a sequential manner. Initially, it orders the connection requests according to some appropriate criterion and then serves the connections on a one-by-one basis. The demands are served in a way that the impact of establishing each demand (lightpath establishment) on the currently established lightpaths will be minimized.

The ***online Rahyab*** is the contributed algorithm for the dynamic or network operation mode. This algorithm is compiled in Chapter 5. *Online Rahyab* is formulated as a multi-constraint IA-RWA problem. In our approach the cost of a link is a vector (and not a scalar) with entries being the individual link impairments and other link parameters. This conceptual approach allows a different and more efficient handling of the impairments. *Online Rahyab* uses the Multi-Constraint Path (MCP) framework based on a single mixed metric for computing a couple of candidate paths between source and destination nodes, for a dynamic demand. This strategy could be based on the well-known Dijkstra shortest path algorithm. Furthermore, this MCP engine can be exploited for diverse routing for protection purposes (e.g., 1+1 protection) or generic *k*-shortest path algorithms. The performance of proposed algorithm is compared with other online IA-RWA algorithms. A variation of this algorithm, which considers the availability of the optical performance/impairments monitors in the network within the routing and wavelength assignment process to compensate for the inaccuracies of the QoT estimators is also presented.

The design and development of DICONET Network Planning and Opeartion Tool (NPOT) is compiled in Chapter 6. The key innovation of DICONET is the development of a network planning and operation tool residing in the core network nodes that incorporates real-time assessments of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. The modular design of NPOT paved the way to include *offline Rahyab* as the IA-RWA planning module of NPOT. The result of performance evaluation of NOPT and a similar tool (i.e., DIAMOND) is also presented. The conclusions and future works are presented in Chapter 7. The key contributions of this Ph.D. study can be summarized as follows:

- A comprehensive literature survey on impairment aware optical planning and operation. Classification of impairments and the IA-RWA proposals[1].
- Design and development of an offline IA-RWA algorithm for planning of transparent optical networks. The contributed algorithm considers the dedicated path protection demands. The performance of the contributed algorithm is compared with enhanced algorithms from literature.
- Design and development of an online IA-RWA algorithm for the operation mode of transparent optical networks. This algorithm also considers the inaccuracy of the QoT estimation.
- Design and development of the DICONET NPOT. The modular design of NPOT paves the way to consider different modules in an integrated network planning and operation tool. The *offline Rahyab* is included in the NPOT and its performance is also evaluated and reported in this Ph.D. dissertation.

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1 - The contributed publications are compiled in Appendix B.

Chapter 1:

1. Evolution of Optical Networks

Back in the mid-1990s, telecom industry experienced dense wavelength division multiplexing (DWDM), which enables a single strand of optical fibre to carry multiple channels of information using multiple wavelengths of light. In DWDM technology, each wavelength of light requires an optical transceiver to convert an electronic stream of digital data into an optical signal and back again. The cost of optical transport system is dominated by the cost of those transceivers, essentially because optical signals have to be turned into electronic signals and back again to optical domain whenever they need to be routed from one fibre to the next.

The elimination of this conversion between the optical and electronic domain and therefore the required transceivers was the main idea in the late 1990s. This idea led to the concept of optical add-drop multiplexing (OADM) hardware that could route a signal in the optical domain enabling wavelength to add or leave a network node. The initial OADMs were fixed devices and only pre-determined wavelengths could enter or leave the node. In order to increase the level of flexibility, networks would have to include optical equipment that could be programmed from a remote network operation centre, enabling an operator to change the routing on demand. The reconfigurable OADMs could save operating cost by eliminating the need to send a technician to a network node to install or configure the optical equipment. The ultimate vision could be a flexible and dynamic optical network, in which an operator could simply call for network capacity without worrying about the physics of the underlying optical link.

Realizing the 1990s dream of fully automated and flexible networks has proven more difficult than expected. The first reconfigurable OADM (Marconi's SmartPhotonix PMA-32 ROADM) supported 32 wavelengths flowing in two directions, usually labelled 'east' and 'west', and could be used in a point-to-point or ring network topology. This ROADM used a 'broadcast and select' architecture, which meant splitting the incoming optical signal between the drop and straight-through paths, and then using wavelength blockers to eliminate individual wavelengths on each path. On the add ports where signals were injected to the network, banks of tuneable lasers (transmitters) were used to insert new wavelengths. This early ROADM design had two limitations: 1) Lack of architectural flexibility and 2) add/drop ports on the front faceplate were associated with specific wavelengths. Tuneable lasers overcome the latter limitation for the add ports, but dropped wavelengths had to be routed to a specific faceplate port. If that port was not connected to a router, then a technician would still need to go to the network node and change a patch cord manually. However, the former limitation prevented the device to be used in complex network configurations, such as the interconnected rings or mesh topologies that carriers were starting to want so they could increase the efficiency of their networks. In fact, a mesh network is more robust in the event of failure because there are more alternative routes across the network to choose from; it also enables more efficient use of capacity, by allowing carriers to route traffic away from hotspots to links that are less heavily used. New ROADMs are being developed that are not restricted in wavelength or port or direction, and so can support mesh networks. These next-generation ROADMs may help enable the flexible optical networks that were promised more than a decade ago.

Next-generation ROADM equipment is the fastest growing segment of the optical equipment business. This growth has been enabled because of developments in two key optical components: the tuneable lasers and the wavelength-selective switching (WSS) technology. Although there are many applications for tuneable lasers, one of the most important once is in the latest generation of ROADMs. WSS can route each incoming wavelength independently to one of many output ports as depicted in Figure 1-1. WSS modules are the building blocks for ROADMs that can handle any wavelength on any port (and so are known as 'colourless') and can connect signals flowing in any direction on any port to any other port (hence 'directionless'). Three WSS modules are needed to support each connection on a colourless ROADM. This means that a colourless ROADM for use in a node on a ring needs six of the switches, while a ROADM for use in a four-connection node on a mesh network would need 12 switches.

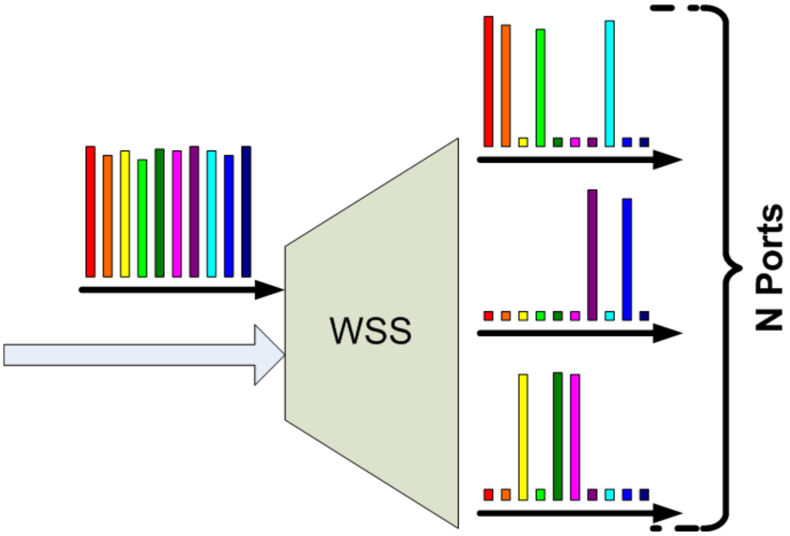

Figure 1-1: WSS can route any wavelength of incoming signal to any of its output ports.

Although the optical components for flexible networks are maturing, the intelligent control software still needs work. The main candidate to control optical networks is an established protocol called Generalised Multi-protocol Label Switching (GMPLS). It offers many of the key functions necessary, such as the ability for a network node to discover the topology of its nearest neighbours and to deliver real-time inventory reports, which show exactly where equipment and bandwidth are available in the network. The protocol also enables, among other things, service creation, routing optimisation and automatic protection switching. Through GMPLS, control software can understand the resources that are available in the network. The software can also be programmed with information about any constraints that exist, especially in the optical domain, so that it can route around them. Routes may be selected to promote geographic diversity (e.g., diverse routing), or to save cost and/or energy. In all-optical networks, certain links could also be excluded from use in complex routes because the overall Quality of Transmission (QoT) would be below a certain threshold. There's always been a trade-off between flexibility and distance, because the analogue optical signal gradually degrades and will eventually need to be regenerated.

Historically, the contents of each wavelength have undergone electronic processing at different nodes in the network. As the size of the network is increased, this necessitated the use of a huge amount of electronic terminating and switching equipment, which presented challenges in cost, power consumption, space requirements, heat dissemination and maintenance. Since optical technology can operate on a spectrum of wavelengths at once, and can operate on wavelengths largely independently of their data rate, maintaining signals in the optical domain allows significant amount of equipment to be eliminated from the network and provides a scalable path for network growth.

The hierarchy of optical networks, layered architectural model, configurable optical networks and eventually network planning and operation processes are compiled in the rest of this chapter.

1.1 Hierarchy of Optical Networks

Optical networks can be segmented into multiple geographical tiers, with key differentiator among the tires being the number of clients served, the required bandwidth, and the geographical coverage of the network. One such segmentation is depicted in Figure 1-2. At the edge of the network, closest to the end-users, the access tier is located. This tier distributes/collects traffic to/from the clients of the network. Access networks generally serve tens to hundreds of clients and span a few kilometres. The metro-core tier is responsible for aggregating the traffic from the access networks, and generally interconnects a number of central offices. A metro-core network typically aggregates the traffic of thousands of clients and spans tens of hundreds of kilometres. Moving down the hierarchy, several metro-core networks are interconnected via regional networks. A regional network carries the portion of the traffic that spans multiple metro-core domains, and is shared among hundreds of thousands of clients. The geographical coverage of metro-core networks extend to several hundred to a thousand kilometres. Inter regional traffic is carried by the backbone network. Backbone networks may be shared among millions of customers and typically spans thousands of kilometres. The characteristics of a tier are important in selecting an appropriate technology. For example, whereas the backbone network requires optical transport systems with very large capacity over long distances, that same technology would not be suitable, not would it be cost effective in an access network. The particular implementation may also differ across tiers. For instance, with respect to WDM technology, backbone networks generally have a 80 to 160 wavelengths per fibre, regional networks have roughly 40 to 80 wavelengths per fibre, metro-core WDM networks have anywhere from 8 to 40 wavelengths per fibre and access networks typically have no more than 8 wavelengths.

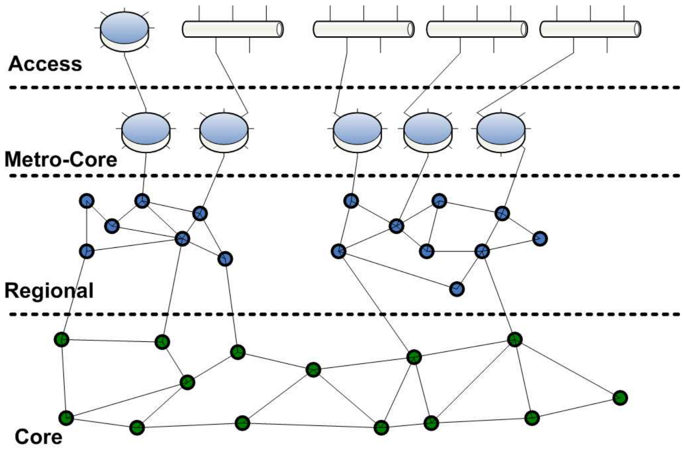

Figure 1-2: Networking hierarchy.

There is a recent trend in telecommunication industry to ‘blur the boundaries’ between tiers in the mentioned hierarchy. Telecom operators are looking for technology platforms that are flexible enough to be deployed in multiple tiers of the network, with unified network planning and management system to simplify operations [CS07].

1.2 Layered Model

Layered network architecture is shown in Figure 1-3. The application layer on top includes all types of services, such as voice, video, and data. The intermediate layer encompasses multiplexing, transport and switching based on electronic technology. For instance, this layer includes the Internet Protocol (IP) routers, Ethernet switches, and Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) switches. Each of these protocols has a particular method for partitioning data and moving it from source to destination.

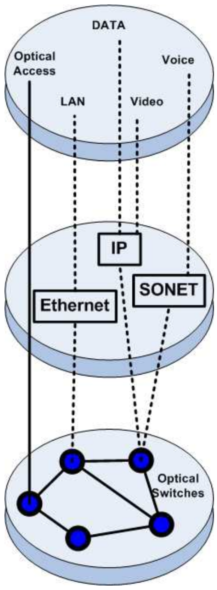

Figure 1-3: Layered architecture model.

The payloads of the electronic layer are passed to the optical layer, where they are packed into wavelengths. In this model, the optical layer is based on WDM technology and utilizes optical switches that are capable of dynamically routing wavelengths. Thus, the bottom level of this model can also be considered as the 'configurable WDM layer'. Note that it is possible for the application layer to directly access the optical layer, as depicted in Figure 1-3 by the optical access services. This capability could be desirable to transfer very large streams of protocol and format independent data. By transporting the services completely in the optical domain, the optical layer potentially provides what is known as protocol and format transparency. However, so far these services are not materialized in practical networks.

One issue with carrying services directly in wavelengths is that the network can be difficult to manage. Network operations can be simplified by using standard framing that adds overheads for management. For instance, the SONET and SDH specifications define a standard framing format for optical transmission, where the frame includes overhead bytes for functionality such as performance monitoring, path trace and Operation, Administration, and Maintenance (OAM) communication. SONET/SDH is commonly used as the interface to the optical layer; standards exist to map services such as IP into SONET/SDH frames.

Compared with SONET/SDH, the Optical Transport Network (OTN) architectural paradigm provides benefits such as more efficient multiplexing and switching of high bandwidth services, enhanced monitoring capabilities, and stronger forward error correction (FEC). OTN provides a uniform method of multiplexing a range of protocol types, essentially by providing a generic digital wrapper for the payload. It is envisioned as a step towards network convergence, where carriers can support multiple services with a single network rather than deploying parallel networks. OTN has gradually entered commercial market; however, there is still a great deal of deployed legacy SONET/SDH-based equipment.

1.3 Configurable Optical Networks

The initial driver for automated configurability of the optical networks was the normal uncertainty in traffic demand forecasts and churn that occur in a network. Churn is the process of connections being established and then later torn down as the demand pattern change. It is difficult to forecast the precise endpoints and bandwidth of the traffic that will be carried in a network. Furthermore, while most of the traffic has historically been fairly static, with connection holding times on the order of months or longer, there is a subset of the traffic that has a much shorter lifetime, leading to network churn. Besides, as operators move away from protection schemes where the backup paths are pre-established, configurability is needed to dynamically create a new path for failure recovery (i.e., restoration).

Therefore, it is desirable that the network is able to adapt to the demand prediction inaccuracies, changing demand patterns, and network failures; moreover, it is necessary that the process be automated to eliminate the labour cost and potential errors involved with manual intervention and configuration. The infrastructure and distributed intelligence to enable automated configurability are collectively known as the control plane. This is in contrast to the typically centralized management plane that has traditionally been responsible for network operations such as fault, accounting, performance and security management.

Various organizations have developed standards in support of the control plane. For instance, the ITU has developed the Automatically Switched Optical Networks (ASON) architecture, and the Internet Engineering Task Force (IETF) has developed Generalized Multi-Protocol Label Switching (GMPLS) paradigm. These specifications and standards include signalling protocols to automate control of the optical network resources, and connection establishment. Some of the relevant standards and specifications can be found in [SDI04], [RFC3945], and [ITU06]. A more detailed discussion of this topic can be found in [BRS03].

GMPLS includes three models for interacting with the optical layer: peer, overlay and augmented. In the peer (or integrated) model, the IP (or other elements of electronic layer) and optical layers are treated as a single administrative domain, with IP routers having full knowledge of the network topology. The IP routers can determine the entire end-to-end path of a connection including how it should be routed through the optical layer. In the overlay model, the IP and optical layers are treated as distinct domains, with no exchange of routing and topology information. The IP layer is essentially a client of the optical layer and requests bandwidth form the optical layer as needed. The augmented model is a hybrid approach where a limited amount of information is exchanged between layers.

Given the amount of information sharing in the peer model and the potential trust issues between the layers (e.g., the IP and optical layers may be operated by different operators), the overlay and augmented models are generally more favoured by telecommunications operators. In the overlay model, the boundary between the client and the optical layers is called the User-Network Interface (UNI). Signalling specifications for the UNI have been developed by the IETF as well as the Optical Internetworking Forum (OIF) [SDI04], [OIF04].

As protocols for automated configurability (e.g., GMPLS) have begun to make their way into operator networks, the need to support more advanced dynamic services has emerged. In one flavour of dynamic services, the application requests a connection and requires that it be established very rapidly. For instance in large-scale distributed computing, there may be hundreds of computers that continually need to change their interconnected pattern as the computation evolves. In a second type of dynamic applications, very high-bandwidth transmission is periodically required for a short period of time. The need for the network resources is often known in advance. Grid computing, which is a mean of sharing distributed processing and data resources, is a good example of this kind of applications. This may require that huge data sets be disseminated to multiple locations in a very short period of time.

1.4 Network Planning and Operation

Before planning or operating, a network should be properly designed. The network design phase, encompasses the up-front work such as selecting network nodes, laying out the network topology to interconnect the nodes, selecting the transmission and switching systems to deploy (e.g., choosing the line rate, modulation format, etc.), and what kind of equipments to deploy at a particular node. Network planning is more focused on the details of how to accommodate the traffic that will be handled by the network. For instance, network planning includes selecting how a particular demand should be routed, protected and groomed, and what wavelength in the transmission system spectrum should be assigned to it. In network planning phase, there is sufficient time between the planning and operation process such that any additional equipment required by the plan can be deployed, which typically occurs before a network is deployed. In planning phase, there is usually a large set of demands to be processed at one time. Therefore, the main focus of the planning phase is on accommodating the whole demand set (also known as traffic matrix).

In the operation phase, there is usually little time between arrival of the demand and provisioning, and demands are generally processed one at a time. The assumption here is that the demand should be served using whatever equipment already deployed in the network. Therefore, the operation phase should consider any constraints posed by the current state of the network and deployed equipment. This could force a demand to be routed over a sub-optimal path.

The main focus of this Ph.D. study is on the planning and operation of transparent optical networks with consideration for the physical layer impairments. Therefore in the next two chapters the topic of impairment aware optical networking is presented in more details and in Chapter 3, the physical layer impairments and evaluating the quality of transmission (QoT) will be compiled. These three chapters will pave the way to present the contributed algorithms for planning and operation of transparent optical networks.

Chapter 2:

2. Impairment Aware Optical Networking

During the past couple of years, optical networking has undergone tremendous changes and the trend clearly shows an evolution path towards lower cost (CAPEX and OPEX) and higher capacity. Apart from these costs, there are concerns regarding the physical space requirements, energy consumption and heat dissipation. These changes have been governed by developments of networking capabilities (e.g., more wavelengths, higher line rates) and emerging applications (e.g., tele-presence applications). The optical network evolution was focused on providing more capacity in a cost-effective manner. With respect to the optical transmission systems, this evolution can be translated to denser WDM transmission systems (i.e., 80 to 160 wavelengths per fibre) operating at higher line rates (e.g., 10 Gpbs, 40 Gbps or even 100 Gbps), and coarser granularities at switching level [BSB$^+$08]. Furthermore, providing static and high-capacity pipes is no longer sufficient to address the demands of emerging ***dynamic*** applications. Therefore, a dynamic and configurable optical layer and control plane, which is able to serve dynamic requests, is the direct consequence of the mentioned trend. However, all of these requirements should be addressed utilizing a cost-effective solution.

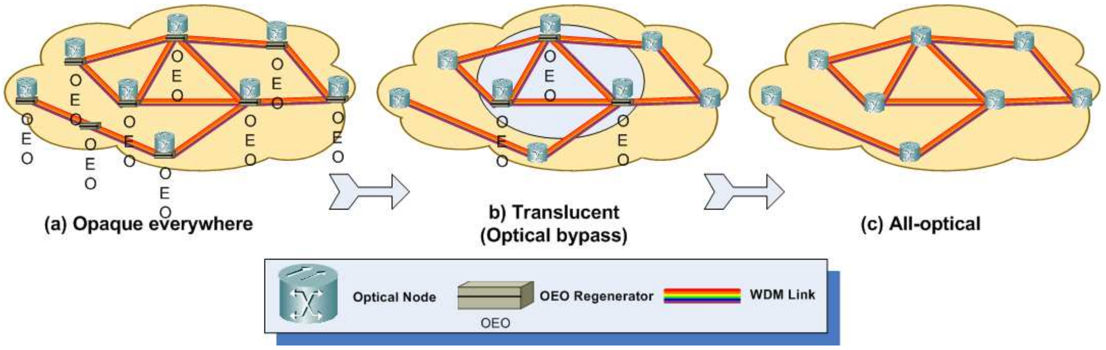

Figure 2-1: Evolution of optical networks: a) Opaque, b) Translucent (optical-bypass), and c) All-optical (Transparent).

Optical network architectures are evolving from traditional opaque networks toward all-optical (i.e., transparent) networks as depicted in Figure 2-1. In opaque networks, the optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every switching (or routing) node. Given the practical and economical considerations, the transmission reach of optical signals is limited (e.g., 2000 to 2500 km) [Sim05]. To go beyond this transparent reach of optics limit, signal regeneration is essential to **r**e-amplify, **r**e-shape and **r**e-time the optical signal (also known as 3R). Regeneration simply improves the quality of the optical signal. The OEO conversion enables the optical signal to reach long distances; however this process is quite expensive due to several factors such as the number of regenerators required in the network, the dependency of the conversion process to the connection line rate and also to the modulation format. An OEO node, especially one based on electronics, will have its own scalability issues related to cost, space requirements, power consumption and heat dissipation. As the size of opaque networks increases, network designers and architects have to consider more electronic terminating and switching equipments, which presents challenges in cost, heat dissipation, power consumption, required physical space, and operation and maintenance costs.

One approach to address these issues is the use of sparsely placed electrical or optical regenerators [STL08]. In principle, regeneration can be accomplished completely in the optical domain (e.g., [SMC+05], [HGB+05]); however, regeneration in the electronic domain (i.e., OEO conversion) is still the most economic and reliable technique. All-optical regeneration is a relatively new technology that is not mature enough and is still an area of active research on many fronts. The lack of practical all-optical regeneration, gives rise to the intermediate optical network architectures, which are identified as translucent [ST07] or optical-bypass [Sal03] networks. Translucent network architectures have been proposed as a compromise between opaque and all-optical networks. In this approach, a set of sparsely but strategically placed regenerators is used to maintain the acceptable level of signal quality from the source to its destination. This approach in fact eliminates much of the required electronic processing and allows a signal to remain in the optical domain for much of its path. Since optical technology can operate on a spectrum of wavelengths at once and also can operate on wavelengths independent of their line rate, keeping the signals in optical domain brings a significant cost reduction due to removal of electronic processing equipments [CDG06]. This removal also paves the way for lower power consumption, heat dissipation and site space requirements. Optical-bypass core WDM networks using reconfigurable optical add/drop multiplexers (ROADMs) and tuneable lasers appear to be on the road towards widespread deployment and could evolve to all-optical mesh networks based on optical cross connects (OXCs) in the coming future. No matter which architecture is considered, the main goal of these architectures is to provide the required infrastructure for end-to-end connection establishment.

In optical networks, a lightpath is an optical path established between a pair of source-destination nodes. The demand set (or traffic matrix) in the network is the collection of lightpaths that must be established. The term “demand” represents an individual request for lightpath establishment. In the context of network planning, some demands are permanent and are referred to as Permanent Lightpath Demands (PLD) or Static demands. The other categories of demands are defined as Dynamic Lightpath Demand (DLD) or Dynamic demands for short, in which demand requests have a finite lifetime (i.e., start and end) [EZK+06]. In this case two variants of DLD can be distinguished (See Figure 2-2):

- Scheduled Lightpath Demands (SLD): The activation time (, date,) and lifetime of these demands are known in advance. Provisioning of layer 1 Virtual Private Networks (VPNs) falls under this category. Since SLDs are pre-planned, they may be considered as a whole during the network planning or operation phase.
- Ad-Hoc Lightpath Demands (ALD): This category of demands is characterized by the fact that their arrival time (, date,) and also their lifetime

are not known a priori. These two parameters (i.e., arrival time and duration) may be modelled in general by two random processes.

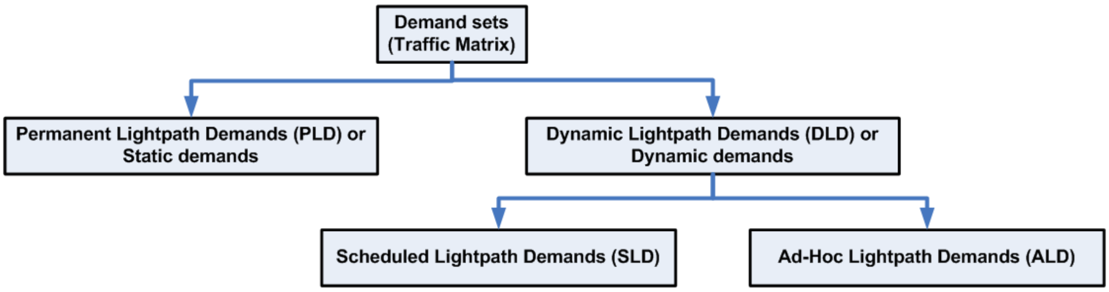

Figure 2-2: Demand set (traffic matrix) categories.

Each lightpath is created by allocating a single wavelength (assuming wavelength conversion is not present) throughout the path. If the allocated wavelength for a given lightpath remains the same across all fibre links that it traverses, then the Routing and Wavelength Assignment (RWA) [ZJM00], [RS95], [Rou01] is said to satisfy the wavelength continuity constraint. However; if a switching node is equipped with a wavelength conversion facility, then the wavelength continuity constraint disappears and the routing problem will be reduced to normal routing in circuit-switched networks, where the only limiting factor is the number of available wavelengths on each link.

Previous studies have already investigated the RWA problem as summarized in [ZJM00]. The RWA problem is known to be NP-Complete. In much of these works, the assumption is that the network is truly all-optical, where all intermediate regenerations (i.e., OEO conversion) are eliminated. Also in most RWA proposals the optical layer is considered as a perfect transmission medium and therefore all outcomes of the RWA algorithms are considered valid and feasible. The reality is that the actual performance of the system may be unacceptable for some of the lightpaths. For this reason the incorporation of physical layer impairments in translucent/transparent optical network planning and operations has recently received some attention from research communities. Either the physical layer impairments (PLI) are considered as constraints for the RWA decisions (i.e., physical layer impairment constrained) or the RWA decisions are made considering these impairments (i.e., physical layer impairment aware). In the latter, it is possible to find alternate routes considering the impairments, while in the former the routing decisions are constrained by physical layer impairments. However, for simplicity, in the rest of this dissertation the generic Impairments Aware RWA (IA-RWA) term is used.

Since the reach of optical signals is limited, some amount of intermediate regeneration is necessary in carrier backbone networks. Therefore the IA-RWA problem will be inevitably coupled with regeneration placement problem [PPK08], in which the network designers are trying to plan and design translucent (or optical-bypass) networks with optimal number of regeneration sites for a given network topology and demand set (i.e., traffic matrix). The regenerator placement problem is also known to be NP-Complete [PPK08], [ZJM00].

The key contributions of this Ph.D. study are novel algorithms for planning and operation of optical networks. In order to report the state-of-the-art and current proposals for impairment aware optical networking, more than a hundred recent papers, and considering 28 different metrics, were collected, reviewed and ranked. The result of this study is compiled in this chapter, as an introduction to impairment aware optical networking. IA-RWA algorithms and their algorithmic approach, classification of IA-RWA proposals, resilience and protection consideration, performance metrics of IA-RWA algorithms, and eventually impairment aware control plane extensions are compiled in this introduction. Discussions and Chapter summary will conclude it.

2.1 IA-RWA Algorithms

In this section, the algorithmic approach for solving the IA-RWA problem and the classification of the different IA-RWA proposals in the surveyed literature is presented. This section also includes a description of the performance metrics and the methods adopted to evaluate the different proposals.

2.1.1 Algorithmic Approach

In general the algorithmic approach for the IA-RWA problem can be categorized either as sequential approach based on some heuristic or meta-heuristic algorithms, which usually give a sub-optimal solution, or combinatorial approach, which searches for an optimal solution.

The classic RWA problem (i.e., without physical layer impairments constraints/awareness) is NP-complete [ZJM00] and thus its optimal solution cannot be found in polynomial time using any known algorithm. The IA-RWA problem introduces additional difficulty to the RWA problem since it involves a number of physical layer-related constraints. To tackle these obstacles the RWA problem can be decomposed into two sub-problems, namely, a routing (R) problem (i.e., choice of a suitable path) and a wavelength assignment (WA) problem (i.e., allocation of an available wavelength for the selected path). Then each problem can be solved separately. When treating routing and wavelength assignment steps separately and individually, each step can be further broken into two components: (1) search and (2) selection. The first step concerns the search for a set of candidate paths/wavelengths, which may be also the subject of appropriate ordering consideration. The second step is a decision function that operates on the given candidate set.

As already mentioned, further simplification of the IA-RWA problem can be achieved with the application of a heuristic (or meta-heuristic) algorithm, which can be used to solve any of the R and/or WA sub-problems. Although such a decomposition of the RWA problem does not guarantee its optimal solution, still the computation time can be reduced considerably.

2.1.1.1 Heuristics

Since the IA-RWA problem involves additional physical-layer constraints, which in most cases are verified using complex analytical models of physical impairments, the complexity of the proposed algorithms are significantly important. Therefore most of the IA-RWA algorithms, reported in the literature are based on simple heuristics.

Regarding the routing sub-problem, a variety of heuristic algorithms can be found in the literature and, in general, they are based on the shortest path (SP) routing algorithm (e.g., Dijkstra algorithm). Among these algorithms, two classes of algorithms can be distinguished, namely, single-path routing algorithms and multi-path routing algorithms. The latter are also known as *k*-shortest path (*k*-SP) algorithms. In any SP-based algorithm there is a cost (or weight) parameter assigned to each network link. This parameter should have additive properties and it is used by the algorithm to find a path of a minimum overall cost. The link cost may simply represent a hop distance (i.e., unique and similar cost for all links) or it may correspond to the link state and then it involves link congestion or physical impairment-related information.

Regarding single-path routing, a number of IA-RWA proposals follow the minimum hop SP approach as reported in [PPK08], [RDF$^+$99], [PCB$^+$07], [HHM05], [CMS$^+$04], [CCM06] , [ZNC07], [HBP$^+$07] and [HBS^{3}07]. As for the calculation of PLI-aware link costs, the simplest metric which has additive properties is the physical distance [ZNC07]. Other IA-RWA algorithms use the link cost that is a function of the residual dispersion parameter [CMS$^+$04], the Four Wave Mixing (FWM)[1] crosstalk [MMK08], the Q-factor [ZNC07], or the noise variance [HBP^{2+}07]. In this last case, both linear and non-linear impairments are represented by the noise variance. This solution may be preferable since noise variances are additive hop by hop.

Some IA-RWA methods introduce modifications to the SP routing algorithm. For instance, the Minimum Coincidence and Distance (MINCOD) algorithm [MSM$^+$07] computes the paths that minimize the distance and the number of shared links, while the Least-Congested algorithm [CCM06] aims at balancing the network load. Besides, an impairment-constraint-based SP algorithm, which takes into account the utilization of network resources and the physical impairment due to FWM crosstalk, was proposed in [MMK08]. Finally, an adapted Bellman-Ford shortest path algorithm that deals with multi-objective, constraint-based lightpath provisioning was proposed in [CCM05].

IA-RWA algorithms based on multi-path routing algorithms operate on a set of pre-calculated alternative paths. Since these paths are in usual the shortest paths, such class of multi-path algorithms can be also referred to as *k*-Shortest Path (*k*-SP) algorithms. In some cases the set of candidate paths is restricted to disjoint paths [PPK^{2}08].

Similar to the single-path routing, in the multi-path routing the cost metric can be related to the hop count as utilized in [EZK$^+$06], [SYZ$^+$07], [YR05], [MST^{2+}07], and [CAV$^+$04] or can be PLI-aware. The distance metric is the simplest PLI-aware link cost ([PPK^{2}08], and [PZW$^+$08]). Also, other physical impairments, such as Polarization Mode Dispersion (PMD), Amplifier Spontaneous Emission (ASE) noise, Crosstalk (XT), Chromatic Dispersion (CD), and Filter Concatenation (FC), can be adopted to represent the link cost [TVM$^+$04]. Besides, many proposals consider a Q-factor as a link cost. This cost can be based on real-time Q-factor measurements collected from devices [DS05] or can be calculated analytically either as the worst

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1- The physical layer impairments (including Four Wave Mixing) are presented in great detail in Chapter 3.

case Q-factor penalties [PPK²08] or taking into account linear [KTM⁺05] and non-linear impairments [MST⁺07]. More complex link cost formulations may combine a number of parameters, such as information about regenerating modules, the number of available and total wavelengths, and the link length [YSR05].

Once candidate paths are found, the selection of an appropriate path is performed either sequentially or in parallel. In the former a sequence of re-attempts is performed until the first available path that complies with the given performance requirements is found [YR05], [CAV⁺04], [CPV⁺07]. In the latter the path, which is the most suitable according to a given decision criteria is selected [SYZ⁺07], [JF04]. The search among multiple alternative paths can be implemented by the Breath-First Search (BFS) algorithm [YR05], and [JF04]. BFS tries to examine all nodes of a network graph in some systematic way in order to explore all possible solutions.

The wavelength assignment subroutine operates on a set of candidate wavelengths that are given on a previously selected routing path (or paths). The set may be ordered, according to a given policy, or unordered, i.e., the wavelengths are treated in a round-robin way. Wavelength ordering was proposed in [HB06] as a technique to select the wavelength with lower number of adjacent-port crosstalk terms. As an extension to this method, the WA algorithm in [HBP⁺07] initially considers the wavelengths that are most separated in terms of frequency. Then wavelengths are analyzed in an optimal order to maximize the frequency separation.

Given a set of candidate paths, the wavelength selection phase can be performed either sequentially or in parallel. This is similar to the routing sub-problem. In the sequential approach, the first non-occupied wavelength that satisfies network-layer and physical-layer constraints is selected. Such a First-Fit (FF) selection method has been considered in a large number of IA-RWA proposals [EZK⁺06], [PPK08], [CCM05], [PCB⁺07], [CMS⁺04], [MBA⁺03], [YSR05], [CCM06], [YR05], [HBP²⁺07], [HK05], [SYZ²⁺07], [PW06], and [PZW⁺08]. On the contrary, some IA-RWA algorithms try to look through all of the candidate wavelengths so as to find the Best-Fit (BF), i.e., the most appropriate one [CCM05], [HHM05]. For instance, the wavelength of the lowest utilization in the network can be selected based on the network state information given at the sources node, as in the Least-Loaded algorithm [MSM⁺07]. Finally, a random selection, which means choosing randomly amongst the available wavelengths, can be performed [RDF⁺99], [HBP²⁺07]. It is well known that wavelength blocking probability of a random WA algorithm is worse than that of the FF algorithm [ZJM00]. Nonetheless, since the random algorithm tends to spread the wavelength use across the network, the crosstalk effects might be limited [RDF⁺99].

Some of the proposed WA algorithms make a decision based strictly on physical layer impairments. An example can be a PLI-aware algorithm presented in [MMK08] which aims at minimizing the FWM crosstalk effect. This algorithm has been proposed in two versions, namely, to perform either FF or BF wavelength selection. Another two algorithms can be found in [PBD⁺06] and while one of them focuses on the selection of the lightpath with the highest Q-factor, the other addresses the fairness issue and it also minimizes the impact of this lightpath on the already established lightpaths.

Apart from separate R and WA solutions, there are some heuristics that intent to solve the IA-RWA problem jointly. To achieve this goal the A^* algorithm, which is a shortest path algorithm derived from the Dijkstra algorithm, has been proposed in [MBL^{+}08]. The $A*$ algorithm relies on a layered network graph that is derived from a network graph by multiplication of links and vertices by the number of corresponding wavelengths. Thanks to the layered representation of links and wavelengths in a single graph the algorithm is able to find an appropriate lightpath in one algorithmic step.

Another example can be the Minimum Crosstalk (MC) algorithm [ZPS^{+}07]. For each wavelength, MC runs a SP algorithm to find candidate routes. The link weights are constant and equal to the physical link lengths. For each candidate route, the number of crosstalk components along the route is calculated. Among all the candidate routes, it chooses the route at the wavelength with the minimum crosstalk intensity.

Finally, the Best-OSNR algorithm that jointly assigns to a given request a path and a wavelength in order to maximize the OSNR was proposed in [CCM06]. In Table 2-1 the reported heuristic algorithms are summarized.

Table 2-1: Heuristic algorithms in IA-RWA

(Sub-)Problem	References
Routing	
Single-path	
Hop-based Shortest Path	[PPK08], [RDF^{+}99], [PCB^{+}07], [HHM05], [CMS^{+}04], [CCM06], [ZNC07], [HBP^{+}07], [HBS^{3}07]
PLI-aware Shortest Path	[CMS^{+}04], [ZNC07], [MMK08], [HBP^{2+}07]
Modified Shortest Path	[CCM05], [MMK08], [MBL^{+}08], [MSM^{+}07], [CCM06]
Multi-path (route calculation)	
Hop-based k-SP	[EZK^{+}06], [SYZ^{+}07], [YR05], [MST^{2+}07], [CAV^{+}04]
PLI-aware k-SP	[PPK^{2}08], [YSR05], [KTM^{+}05], [MST^{+}07], [TVM^{+}04], [PZW^{+}08]
Multi-path (route selection)	
Sequential (re-attempt)	[YR05], [CAV^{+}04], [CPV^{+}07]
Parallel (best one)	[SYZ^{+}07], [JF04]
Wavelength Assignment	
First-Fit	[EZK^{+}06], [PPK08], [CCM05], [PCB^{+}07], [HHM05], [CMS^{+}04], [MBA^{+}03], [YSR05], [DS05], [CCM06], [YR05], [HBP^{2+}07], [HK05], [SYZ^{2+}07], [PW06], [PZW^{+}08]
Best-Fit	[HHM05], [CCM05]
Least-Loaded	[MSM^{+}07]
Random	[RDF^{+}99], [HBP^{2+}07]
PI-aware	[MMK08], [PB06], [PZW^{+}08], [PBD^{+}06]
Routing and Wavelength Assignment	
Minimum Crosstalk	[ZPS^{+}07]
Best-OSNR	[CCM06]

2.1.1.2 Meta-heuristics

Apart from the heuristic-based algorithms, there is a class of IA-RWA algorithms that exploit meta-heuristic methods. Meta-heuristics are very attractive as far as they do not involve complex mathematical formulations and, at the same time, they allow the convergence to an optimum solution through successive iterations.

The Ant Colony Optimization (ACO) is one of meta-heuristics applied to solve the IA-RWA problem [LS05], [PW06], [PZW+08]. ACO is characterized by ant-like mobile agents that cooperate and stochastically explore a network. The agents build iteratively solutions based on their own information and on the traces (called pheromones) left by other agents in network nodes. In the proposed IA-RWA method, the ACO algorithm calculates the path on a hop-by-hop basis. The next hop is calculated based on pheromone values of the node, which accounts for the OPM of the links. The algorithm is capable of the distributed calculation of a multi-constrained path under restrictions resulting from ASE noise and optical power budget.

Another IA-RWA algorithm [LCA03] makes use of a Genetic Algorithm (GA). A GA operates on a set of solutions called population. In each of iterations appropriately selected solutions from one population are used to form, through a number of operations, a new population that is expected to be a better one. The proposed IA-RWA algorithm attempts to compute a lightpath in such way that the average blocking probability and the usage of optical devices, such as wavelength converters and amplifiers, is minimized. Both ASE noise and PMD are considered as physical impairments.

To solve the problem of survivable lightpath provisioning in a translucent network the Tabu-Search (TS) meta-heuristic has been applied [YSR05]. TS is a neighbourhood search method which tries to avoids local minimum by accepting worse solutions and by using the solutions' search history. In the proposed solution, the TS algorithm operates on a set of *k*-SP, where *k* is dynamically changing according to the direction of improvement. This adaptive feature improves the efficiency of the method. As for the physical layer impairments, both PMD and ASE noise are used.

Finally, in [MSM+07] the authors propose a Predictive Algorithm (PA) for the IA-RWA problem. The main idea of this algorithm is to apply the branch prediction concept originally used in the computer architecture area. In optical networks, the algorithm selects the lightpath based on the history of previous connection requests. The main advantage of this algorithm is that it can be used in distributed routing and it does not need any update messages with global network information in order to compute the lightpath. The physical impairment considered by this algorithm is the maximum transmission distance. Meta-heuristic algorithms are summarized in Table 2-2.

2.1.1.3 Optimization methods

The last class of methods considered for IA-RWA is based on the network optimization theory. The network optimization methods are usually appropriate for off-line optimization of network resources as well as for on-line and centralized lightpath provisioning. Among the solutions presented in the literature, most of them have been proposed for transparent networks.

In [TVM+04] a link-path formulation to solve an Integer Linear Programming (ILP) problem of RWA in a transparent network is proposed. A set of *k* paths is pre-calculated with the assistance of a SP algorithm, which uses either a single physical impairment [TVM+04] or a Q-Penalty [KTM+05] as the link cost parameter.

Presented ILP formulation takes into account the existence of sparse wavelength-conversion capable nodes in the network.

Some more specific problems involving PLI constraints into the optimization problem were studied as well. A Mixed-ILP (MILP) formulation for the RWA problem of multicast connections, while considering optical power constraints, is proposed in [HK05]. Authors in [LS05] consider algorithms for the logical topology design and traffic grooming problem in WDM networks with router interface constraints as well as optical constraints. Their approach is based on a linear program which is NP-complete. They also introduce heuristic algorithms which use a graphical modelling tool. Also, an ILP formulation for the problem of traffic grooming in optical virtual private networks with the BER constraint is presented in [SZM$^+$05].

In the case of translucent networks, the problem of regenerator placement with constraints on OSNR is solved using an ILP formulation [ZHP00]. A solution to similar problem, considering BER constraints is reported by applying Dynamic Programming (DP) technique [KS01]. Moreover, the problem of survivability in lightpath provisioning in a translucent network is solved in [YSR05] using an ILP formulation. In this work PMD and ASE noise are considered.

In [CPV$^+$07] the implementation of an LP solver in a Path Computation Element (PCE) is reported. The implemented objective function minimizes the maximum link bandwidth utilization. As a result the routes which satisfy the required constraint in terms of bandwidth and optical signal quality can be found. In Table 2-2 the reported optimization algorithms are summarized.

Table 2-2: Meta-heuristic and optimization algorithms for IA-RWA problem.

Meta-heuristics				Optimization methods		
ACO	GA	TS	PA	M(ILP)	LP	DP
[PW06], [PZW$^+$08]	[LCA03]	[YSR05]	[MSM$^+$07]	[YSR05], [KTM$^+$05], [HK05], [TVM$^+$04], [SZM$^+$05], [ZHP00]	[CPV$^+$07]	[KS01]

2.2 Classification of IA-RWA Algorithms

When selecting a lightpath (route and wavelength), an IA-RWA algorithm for a transparent or translucent network has to take into account the physical layer impairments as well as the wavelength availability. With static traffic (i.e., network planning), the entire set of connection requests is known in advance, and the static (off-line) RWA problem of setting up these connection requests is named the Permanent Lightpath Establishment (PLD) problem. In a dynamic traffic scenario, the connections are requested in some random fashion, and the lightpaths have to be set up as needed (introduced as SLD or ALD). In static (off-line) case, there is enough time between the planning and provisioning (i.e., actual lightpath establishment) processes such that any additional equipment required by the plan can be deployed. In this context, the main goal is to accommodate the whole demand set. In dynamic traffic scenario, there is little time between planning and provisioning, and demands are generally processed one at a time. It is assumed that the demand set must be accommodated using whatever equipment is already deployed in the network. Thus, the IA-RWA proposal must take into account any constraints posed by the current state of the network, which may force a demand to be routed over a sub-optimal path. One big challenge for IA-RWA algorithms is the Quality of Transmission (QoT)-

awareness, in the sense that they must ensure (during admission control) that all lightpaths in the network meet a QoT constraint (e.g., BER) without disrupting previously established lightpath.

The effect of the existing connections in the IA-RWA decision is rarely taken into account in the proposed algorithms in the literature. Some works address this problem considering the crosstalk due to the already established connections [ZPS+07], [PB06], and [HBP+07]. For example in [PB06], the HQ (Higher Q) and MMQ (Maximize Minimum) algorithms try to minimize the effect of new crosstalk when establishing a lightpath. The MC (Minimum Crosstalk) [ZPS+07] wavelength assignment selects the wavelength with minimum crosstalk intensity due to the already established connections. A different approach is considered in [HBP2+07], where, in the lightpath selection, the BER of the selected and affected lightpaths are taken into account in the lightpath establishment. Few works address the problem of selecting the lightpath considering the effect of selected lightpath on the possible future demands. In [ZOG06] and [CMS+04], the Dispersion Optimised Impairment Constraint-based (DOIC) IA-RWA algorithm assigns the wavelength with the lowest residual dispersion. This is done to increase the wavelength availability for the upcoming demands.

The re-routing feature is even rarer than the effect of the existing connections on upcoming demands, mainly due to its complexity. Re-routing refers to the re-computation and re-establishment of already established connections when a new lightpath is established. In [LTG+08], re-routing is utilized to perform the restoration of Label Switched Paths (LSPs) channels based on a threshold of the OSNR values.

There are several heuristic algorithms proposed in the literature dealing with the wavelength assignment sub-problem, such as Random, First-Fit (FF), Least-Used (LU), etc [ZJM00].

When the PLIs are introduced in the RWA algorithms, three main approaches have been considered in the recent literature: a) Compute the route and the wavelength in the traditional way and finally verify the QoT of the selected lightpath considering the physical layer impairments; b) Considering the PLI values in the routing and/or wavelength assignment decisions and c) Considering the PLI values in the route and/or wavelength assignment decision and finally also verify the quality of the candidate lightpath. These cases and their various combinations are depicted in Figure 2-3.

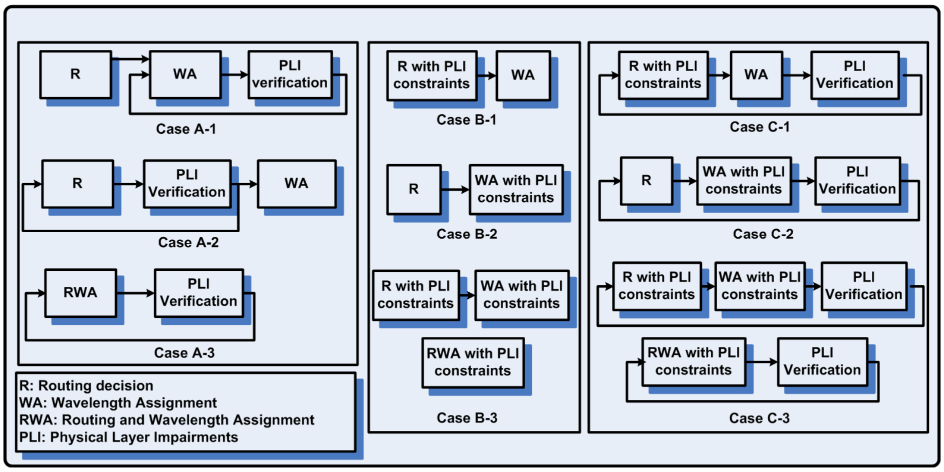


Figure 2-3: Various IA-RWA approaches.

In case A-1 the route and the wavelength are selected without considering the PLI constraints, but after the verification phase, the wavelength assignment decision can be modified. In case A-2 the route is computed without taking into account the physical impairments, but there are re-attempts of computing the route if the PLI constraints are not met for the candidate route(s); finally there is a final phase of traditional wavelength assignment. In case A-3 the route and the wavelength are computed using classical RWA algorithms that are unaware of the PLI constraints (selecting both route and wavelength in one step or selecting first the route and then the wavelength) and there is a final step of checking the PLI constraints in order to possibly change the RWA decision.

Different works (e.g., [PPK08], [JF02], and [SYZ$^+$07]) have followed the A-2 approach. In [PPK08], a combination of IA-RWA algorithm and regenerator placement for dynamic traffic is proposed. This algorithm computes paths between any combinations of nodes under the constraint of a minimal Q (Quality) value. Authors in [JF02] propose a modification of the Bellman-Ford algorithm to compute the path with the minimum number of hops with a certain (monetary) cost limit. At destination the physical layer requirements with different levels of agreement are checked. Also for static traffic, the proposed algorithm in [SYZ$^+$07] computes *k*-Shortest Paths considering the costs of the links associated with impairments and OEO devices; the final path is chosen in a way that satisfies a minimum Q value. The path establishment process is also taken into account in [SYZ$^+$07] and two methods (sequential and parallel) are compared. In the sequential method, the source node sends out a single PATH message containing optical properties which are checked at destination; if the source node receives back a Path-Error message it will try another path from the list of candidate paths. In the parallel method, the source node sends out *k* PATH messages and the destination node makes the path selection.

The A-3 approach is utilized in [EZK$^+$06], [MMH04], [MBL$^+$08], [ZPS^{2+}07], [MSM$^+$07], and [HHM05]. The LERP (Lightpath Establishment and Regenerator Placement) algorithm is proposed in [EZK$^+$06] as an IA-RWA and regenerator placement algorithm. It computes *k* alternate paths, then the wavelength is assigned using the FF or Random method; and finally there is a phase of testing the Q values of the lightpath and placing regenerators if any is needed. In [MMH04] the proposed IA-RWA algorithm is simply the SP combined with FF wavelength assignment, then the quality of the candidate lightpath is verified in terms of maximum BER. In [MBL$^+$08], the *A** algorithm is employed for RWA; it computes *k*-SPs and the path is chosen satisfying a minimum Q value and having the smallest cost in terms of fibre and regenerator utilization. A variation of A-3 approach is found in [PCB$^+$07], in this work the wavelength of the path is initially assigned by means of FF algorithm and then the SP for the selected wavelength is computed. Afterwards, the final phase verifies the level of OSNR and the pulse broadening. In [ZPS^{2+}07] the RWA is performed based on the SP algorithm for each available wavelength and then the lightpath with the highest Q value is selected. In [MSM$^+$07], the lightpath selection is done using a predictive approach and taking into account the possible inaccuracy in the wavelength availability information; then a verification of the Maximum Transmission Distance (MTD) achievable for that wavelength is performed. Finally in [HHM05], two phases compute the lightpath. First a lightpath computation step (Best Path selects the SP among all the available wavelengths or FF selects the SP for the first available wavelength) and then a lightpath verification step based on a BER threshold is performed. In case A-1 the physical impairments are only verified in wavelength assignment process and the possibility of selecting other routes to get better QoT is ignored. In contrary in case A-2 different routes are considered to meet required QoT, while eventually the wavelength is assigned without considering the impact of physical impairments. The last case (i.e., A-3) does not verify the impact of physical impairments neither in routing nor in wavelength assignment process. Only the QoT is verified after finding a potential solution and if the answer is not satisfactory the whole process is repeated.

In general the approaches in group B (cases B-1, B-2, and B-3) address the RWA problem considering the physical layer information: in case B-1 the route is computed using PLI constraints; in case B-2 these constraints are considered in the wavelength assignment process; finally in case B-3 the PLI constraints are taken into account in both, route and wavelength selection. Some of the works that present this approach use the physical layer information as weight of the links, in order to compute the minimum cost lightpath.

Sub-case B-1 is found in [CMS$^+$04], [MBA$^+$03] and [YSR05]. In [CMS$^+$04] the minimum cost path is computed, in which the cost is defined as the route distance and the number of consecutive transparent nodes. In [MBA$^+$03] and [YSR05] a variations of approach B-1 is presented, in which the wavelength is initially assigned using the FF algorithm and then the route is computed. In [MBA$^+$03] the selected route is the one with the minimum noise figure for the candidate wavelength and in [YSR05] the route is computed using link cost, which is associated with different PLI constraints.

The Minimum Crosstalk (MC) wavelength assignment in [ZPS$^+$07] follows the B-2 approach. The MC selects the wavelength with minimum crosstalk intensity.

The B-3 variations, where the PLI constraints are taken into account in both route and wavelength selection process, is found in [ZOG06], [DS05], [CCM06], and [PB06]. The DOIC algorithm presented in [ZOG06] considers the PLI constraints related to CD and OSNR in the route decision process, and also the residual dispersion range in the wavelength assignment. In [DS05] the shortest cost path or the *k* link disjoint shortest cost paths are computed considering the Q value as the link cost, which is obtained from real-time Q measurements. Depending on the network conditions the final decision is taken according to the wavelength balancing efficiency or according to the Q-factor value. The Best OSNR RWA algorithm proposed in [CCM06] selects the lightpath with maximum OSNR. In [PB06] two IA-RWA algorithms are proposed, the HQ (Highest Q) and the MMQ (Maximum Minimum Q) algorithms. The HQ selects the lightpath with the highest Q value and MMQ selects the lightpath that maximizes the minimum Q value among the paths that are affected by the establishment of the new lightpath. Note that MMQ takes into account the impact of the lightpath decision on the already established connections (In section 5 the related literature related to this impact is presented). In general different variations of case B (i.e., B-1, B-2, and B-3) consider the impact of physical impairments in routing and/or wavelength assignment process, however this scheme [PB06] does not try to verify the QoT of the solution or find the optimum one.

Case C is a combination of the two previous approaches. The PLI constraints are taken into account in the routing (case C-1), or in the wavelength assignment (case C-2) or in both (case C-3); but there is a final phase of verification of the PLI constraints that enables the re-attempt process in the lightpath selection phase.

Examples of approach C-1 are found in [PPK^{2}08], [SYZ$^+$07], [KTM$^+$05], [YR05], [MST$^+$07], [ZNC07], and [HBP^{2+}07]. Two algorithms proposed in [PPK^{2}08] compute *k*-shortest paths (*k*=3) using as link costs the worst case of Q values. Then, the whole Q value is verified at destination comparing it with a threshold. The Q threshold is an off-line value in case of static routing, or a dynamic Q value, based on current status of the network, for dynamic routing. The third proposed algorithm in [SYZ$^+$07] selects the route between source and destination in a hop by hop manner. In each node the physical feasibility is verified; furthermore some PLI constraints are also checked at the destination. In [KTM$^+$05] *k*-shortest paths are computed considering the network and physical characteristics such as the link costs; finally there is a validation of the PLI constraints considering the Q-factor, among the previously computed paths. A Similar approach is followed in [YR05], where alternate paths are selected by pruning in the topology those links that are not fulfilling the dispersion and ASE constraints. The lightpath selected is the one with least number of links. Moreover, other PLI constraints are checked at destination. In [MST$^+$07] the Q-factor penalty is used as the link cost in the network, in order to compute the k-shortest paths. Finally, the BER is computed and verified at destination; the selected path is the one with lowest BER value considering a BER threshold. The proposed IA-RWA algorithms in [ZNC07] utilizes link costs related to the Q-factor (as 1/Q or 1/Q^2) for computing the SP; then a PLI constraints verification phase considers the availability of the lightpath or otherwise the maximum reachable node. In [HBP^{2+}07] authors propose a variation of sub-case C-1, in which the wavelength is initially selected by means of FF (unaware of PLI constraints) algorithm, and then SP for that wavelength is computed considering the noise variance of the PLI as the link cost. Finally, lightpaths which cause a BER value higher than a given threshold for the new lightpath or for other already established lightpaths are discarded.

In [HBP$^+$07] authors propose the C-2 approach, where the SP is computed unaware of PLI constraints and the wavelength assignment uses a wavelength order considering the PLI constraints. Finally, there is a verification of the quality of the lightpath in terms of minimum Q value. The proposal in [HBS3-07] is very similar to the mentioned approach, however, a BER threshold is considered at the destination to validate the quality of the lightpath.

An example of sub-case C-3, where the PLI constraints are taken into account in both routing and wavelength assignment processes, is found in [MST^{2+}07]. In this work, k-shortest routes are computed considering a Q-Penalty value as the link costs, and the selected wavelength is the one that maximizes the Q value; and finally the Quality of Transmission (QoT) is verified.

Different schemes in Case C (i.e., C-1, C-2, and C-3) not only try to consider the impact of physical impairments, but also verify the QoT of the solutions and also try to find optimum solution. Obviously the cost of this scheme is its complexity (in terms of running time). Table 2-3 provides a summary of these cases and the related surveyed papers.

Table 2-3: Summary of IA-RWA proposals and approaches

Case	Indicative references
Case A-1	N/A
Case A-2	[PPK08], [JF02], [SYZ^{+}07]
Case A-3	[EZK^{+}06], [MMH04], [MBL^{+}08], [ZPS2+07], [MSM^{+}07], [HHM05]
Case B-1	[CMS^{+}04], [MBA^{+}03], [YSR05]
Case B-2	[ZPS^{+}07]
Case B-3	[ZOG06], [DS05], [CCM06], [PB06]
Case C-1	[PPK^{2}08], [SYZ^{+}07], [KTM^{+}05], [YR05], [MST^{+}07], [ZNC07], [HBP^{2+}07]
Case C-2	[HBP^{+}07], [HBS^{3}07]
Case C-3	[MST^{2+}07]

After this summary of recent PLI-RWA algorithms, it worth mentioning that few works ([ZOG06], [ZPS^{+}07], [HBP^{+}07], and [MST^{2+}07]) utilize or propose specific wavelength (WA) assignment algorithms taking into account the PLI constraints. Different combination of the sub-cases presented in Figure 2-3 may also be found in the literature.

2.3 Wavelength Conversion

Apart from the physical-layer constraints usually there is a wavelength-continuity constraint imposed on the RWA problem in optical networks. This constraint means that a given lightpath connection should be composed of identical wavelengths on the links traversed by the lightpath. Such requirement may affect both the network performance and the complexity of RWA algorithm since the setup of a new lightpath is conditioned on the availability of the same wavelength in a number of links. The wavelength-continuity constraint can be relaxed in the nodes that are capable of wavelength conversion, thus improving the connection blocking probability. In practice the wavelength conversion can be realized in switching nodes either by means of a dedicated all-optical device or with the assistance of an optical-electrical-optical (OEO) signal regenerator. The OEO regenerator converts an input wavelength to an electronic signal and then converts it back onto another wavelength. Because all-optical wavelength converters are still immature and very expensive, the OEO wavelength conversion becomes a viable alternative. In addition to potential wavelength conversion and increasing the optical reach of the signal, OEO can provide other functions too. For example, in a network with sub-rate traffic, it is essential to bundle multiple connections together to better utilize the capacity of a wavelength. This bundling process is most effective when the traffic can be groomed at various nodes in the network. The grooming process is typically performed in the electrical domain using OEO conversion. The impact of physical impairment and features of the electrical layer on constrained routing is investigated in [ZNC07].

Most of IA-RWA algorithms do not take into consideration the wavelength conversion capability. The few ones that allow for such a feature deal with a translucent network scenario and *sparse* regenerators that are capable of wavelength conversion [EZK^{+}06], [MBL^{+}08], [YSR05], and [YR05]. The term *sparse* in this case means that the wavelength conversion is available only in selected nodes. In case that the node allows for sharing of wavelength converters between different input and output ports the number of conversions performed at the same time may be restricted.

The usual assumption is that full wavelength conversion, i.e., from any input to any output wavelength is available. On the contrary, wavelength converters with a limited conversion range allow an incoming wavelength to be switched only to a small subset of outgoing wavelengths [TS07]. To the best of our knowledge, the problem of the limited conversion has not been addressed extensively in the literature.

An interesting problem arises in the translucent network scenario and it concerns the optimization of placement of wavelength conversion-capable regenerators. Here the objective is to minimize the connection blocking probability resulting from both physical and network layer constraints. Such a problem was addressed in [ZHP00] and [SGC02] by using some traffic-prediction-based heuristics.

2.4 Resilience and protection

In a transparent (and to some extents translucent) optical network, the impact of a failure propagates through the network and therefore failure cannot be easily localized and isolated. The huge amount of information transported in optical networks makes rapid fault localization and isolation a crucial requirement for providing guaranteed quality of service and bounded unavailability times. The identification and location of failures in transparent optical networks is complex due to three factors: a) fault propagation, b) lack of digital information and c) large processing effort. Main challenges of fault localization in transparent optical networks include the selection of performance parameters to cover the full range of faults while ensuring cost effectiveness and preserving transparency. The placement of monitoring equipment to reduce the number of redundant alarms and to lower the capital expenses, and the design of fast localization algorithms are among challenges of fault localization in transparent optical networks.

It was observed during the literature survey, that very few works have addressed the issue of resilience and protection in the IA-RWA algorithms. Authors in [JF04] propose an approach, which in addition to physical layer impairments and traffic condition, also takes into accounts the path reliability in the framework of a constraint based path selection algorithm. In [ZPS^{2+}07] the effect of physical layer impairments on dedicated path protection schemes is investigated. The performance of dark and lit backup (protection) path is investigated and it is concluded that lit backup scenario introduces significant penalties in terms of blocking probability and vulnerability to failures. In the framework of all-optical networks with various path protection schemes, authors of [ZPS^{+}07] have proposed algorithms that exhibit low blocking probability without high computational complexity. The authors conclude that considering the blocking probability and required processing time, their dark backup algorithm performs better than lit backup; however, lit backup path eliminates the need for signalling and enables faster network recovery. In [MBL^{+}08] authors have proposed the Suurballe algorithm in the layered network graph, in order to find the shortest cycle passing through source and destination and using disjoint nodes. This cycle is then divided into primary and protection path. If no disjoint paths exist, the cycle having the minimum number of common vertices is selected. The work in [YSR05] addresses the issue of survivability in optical mesh networks considering optical layer protection and realistic optical signal quality constraints. Three kinds of resource sharing scenarios, including wavelength-link sharing, regenerator (i.e., OEO) sharing between protection lightpaths, and regenerator sharing between working and protections paths are investigated in this work. In addition to an ILP-based solution, the authors have also proposed a local optimization heuristics approach and a tabu search heuristics to solve this problem.

2.5 Performance metrics

The traditional way of evaluating the performance of the proposed IA-RWA algorithms in the literature has been: the percentage of blocked connections versus the traffic load for dynamic traffic; and for static traffic, the same metric is also reported, as well as the amount of necessary resources (fibres, wavelengths, regenerators, etc).

In a dynamic scenario, the network is designed and the objective is to route the maximum number of connections. For this reason, the percentage of blocked connections (or blocking rate) is used in order to compare the performance of different IA-RWA algorithms.

On the other hand, for a static scenario two possible cases can be found. If the resources of the network are fixed (i.e., number of fibres, wavelengths, regenerators, etc) then the objective is the same as in a dynamic scenario: to route the maximum number of connections. But however, IA-RWA algorithms with static traffic are usually utilized in the design phase of the network. In this case, the objective may be to minimize the number of necessary wavelengths or even, in the case of translucent networks, to minimize the number of required regenerators.

Table 2-4: Evaluation of the proposed IA-RWA algorithms.

Simulation	Hybrid Simulation and/or experiments and/or analytical models
[EZK^{+}06], [PPK08], [RDF^{+}99], [CCM05], [ZOG06], [MMH04], [PPK^{2}08], [MMK08], [JF02], [SYZ^{+}07], [PCB^{+}07], [ZPS^{2+}07], [MSM^{+}07], [HHM05], [CMS^{+}04], [MBA^{+}03], [YSR05], [ZPS^{+}07], [DS05], [CCM06], [PB06], [KTM^{+}05], [YR05], [MST^{+}07], [ZNC07], [HBP^{2+}07], [HBP^{+}07], [HBS^{3}07], [MST^{2+}07], [TVM^{+}04], [JF04], [SYZ^{2+}07], [PW06], [PZW^{+}08], [SGA^{+}06],	[PBS07], [MBL^{+}08], [CAV^{+}04], [CCV^{+}07], [CPV^{+}07], [TMK^{+}08], [LTG^{+}08], [CAV^{+}05],

Few works report different metrics. For example in [CMS^{+}04], authors evaluate their proposal presenting results of regenerator usage and number of necessary transponders. In addition to blocking probability, in [YR05] the results of resource utilization (in terms of average and standard deviation of link, transmitter, receiver and electronic interface utilization) can be found. Moreover authors report results of computational time of the proposed algorithm. In [EZK^{+}06], authors evaluate their proposed LERP algorithm using different metrics. They present usual results of percentage of blocked connection and required number of regenerators, as well as results of lightpath channels used per demand and regenerator repartition in the network. The work in [MBL^{+}08] evaluates the performance of its proposal in terms of computational time, and dimensioning results (i.e., number of required fibres and regenerators). In [YSR05], the computational time (in terms of running time of the algorithm), and also the number of required OEO modules and wavelengths are reported. Finally, in [PZW^{+}08] the impact of crosstalk accumulation on the maximum transmission distance, blocking probability and BER (average value and distribution) and also fairness of the proposed algorithms in terms of blocking probability and BER are reported. A few other papers, consider the lightpath establishment setup time as a performance indicator. For example [CPV^{+}07] addresses the extension of control plane considering the PLI constraints.

Another metric in this survey is the performance evaluation of the proposed IA-RWA algorithm. Most of the papers have evaluated their proposed algorithms using simulation studies. However, some experimental and analytical approaches that are proposed for performance evaluation are also found. Table 2-4 presents the summary of various evaluation techniques that have been considered in surveyed works.

2.6 Impairment Aware Control Plane Extensions

Two different approaches can be followed to address the integration of IA-RWA algorithms in control planes [SCT01], [MPC$^+$06], [CCV$^+$07]. In the centralized approach, a single element stores the complete information of network topology, resource availability, and PLI performance in a central repository. This element is therefore in charge of collecting and updating all these information and also responsible for computing the optimal routes guaranteeing and satisfying the specific set of lightpath requirements such as optical signal quality, latency, etc. The central element could be either the Network Management System (NMS) or a Path Computation Element (PCE) [MPC$^+$06].

In the distributed approach, each node is responsible to compute, setup, and maintain lightpaths using a common and distributed control plane [SCT01]. The nodes can collect the information on the status of the resource availability by means of a routing protocol, execute a RWA solver, and establish the lightpaths by means of a signalling protocol. To include the PLI constraints in the RWA problem, some extensions are necessary to the current signalling and/or routing protocol. Table 2-5 classifies some of the selected papers according to their approach to solve the PLI-RWA problem.

Table 2-5: Classification of the approaches

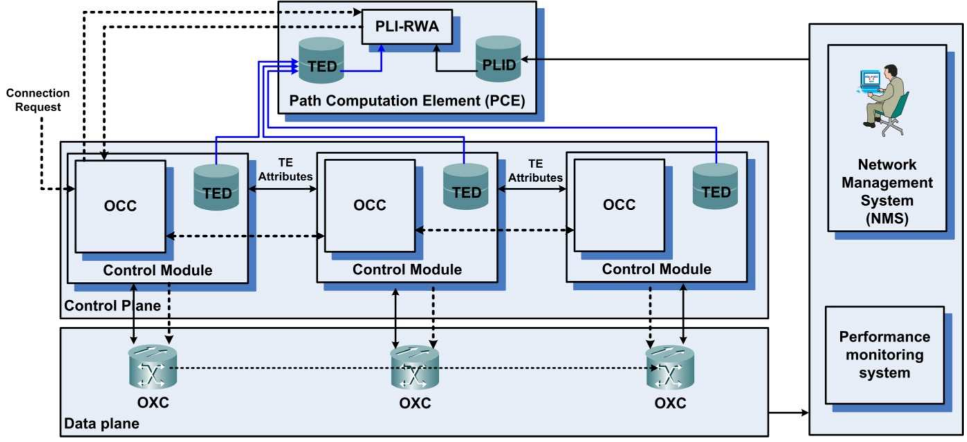
Approach	References
Centralized	[EZK$^+$06], [MBL$^+$08], [CMS$^+$04], [YSR05], [KTM$^+$05], [MST$^+$07], [TVM$^+$04]
Distributed	[PPK08], [CCM05], [ZOG06], [MMH04], [PPK^{2}08], [PCB$^+$07], [MSM$^+$07], [HHM05], [DS05], [YR05], [ZNC07], [HBP$^+$07], [JF04], [PZW$^+$08]
Comparison	[SCT01], [MPC$^+$06], [CCV$^+$07]

The introduction of a control plane (CP) is recognized as a necessary requirement for fast and flexible resource provisioning, easy network operation, and high reliability and scalability. The standardization process for such a control plane is currently being done independently by two different bodies: the Automatically Switched Optical Network (ASON) concept [ITUG8090] developed by ITU and the Generalized Multi Protocol Label Switching (GMPLS) suite of protocols [RFC3945] developed by IETF.

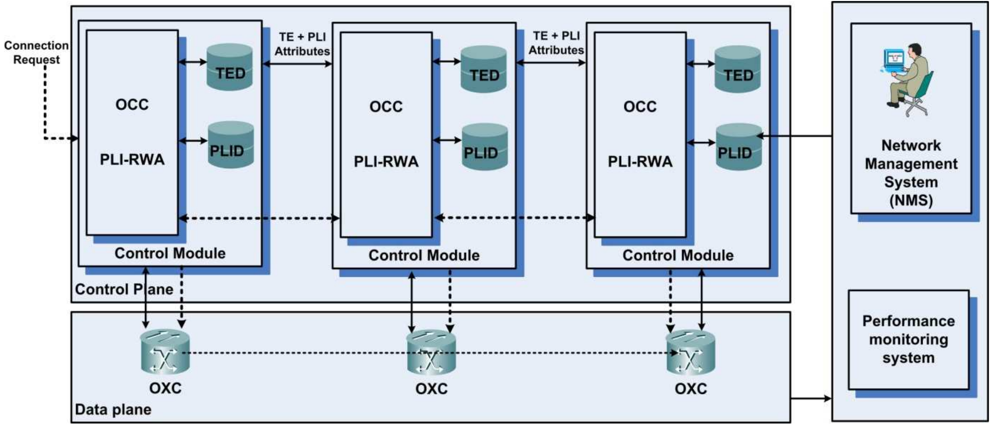
The main benefit of the ASON approach is the definition of the architecture, the requirements and the functionalities of the control plane independently of a particular choice of control protocol. Therefore, a variety of such protocols can be used ranging from the ATM family to MPLS and GMPLS ones.

Contrarily, GMPLS focuses on the implementation of the control plane, involving signalling (RSVP-TE), routing (OSPF-TE), and resource management (LMP) functions and protocols.

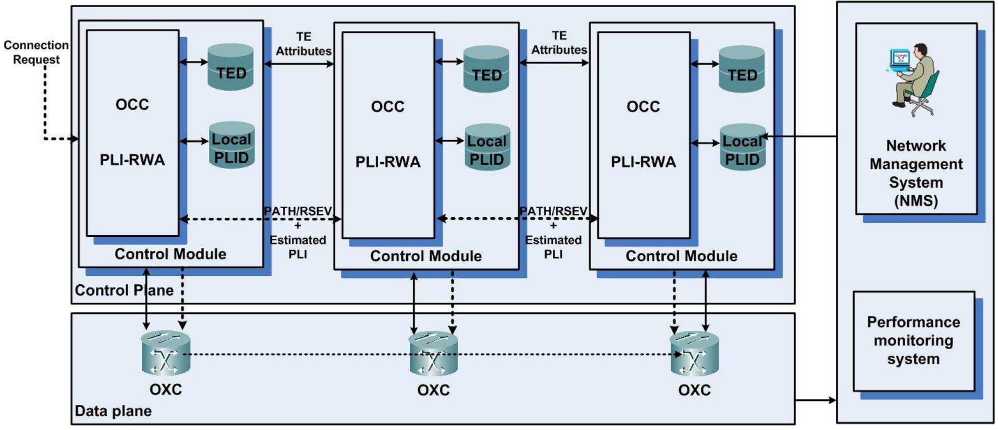
Although both GMPLS and ASON approaches for CP in optical networks are relatively mature and key standards are already available, they do not include any information related to physical impairments and thus are unaware of quality of optical signals. Some recent works deal with the problem of encompassing the PLI constraints into the GMPLS CP functionalities. Three different models have been proposed (see Figure 2-4), namely the Path Computation Element (PCE) model, the Signalling model and the Routing model.



a) PCE model



b) Routing model



c) Signalling model

Figure 2-4: Physical layer impairment aware control plane extensions[1].

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1 - OCC is the optical Connection Controller, and OCX is a typical Optical Cross Connect

2.6.1 Centralized Approach

This integration approach (Figure 2-4(a)) has been first proposed in [CPV+07] and is based on the computation of the PLI-RWA problem in a centralized way utilizing a PCE element. PCE is defined in [RFC4655] as an entity that is capable of computing a network path or route based on a network graph, and of applying computational constraints during the computation. Its aim is hence to perform complex centralized route computation on behalf of the control module of the nodes.

In such a model, the PCE stores two databases. The first one is the Traffic Engineering Databases (TEDs), which are located in the nodes. The second one is the centralized TED, which is updated from former TEDs through a standard, distributed routing protocol. The other database is the PLI database (PLID) obtained by the Network Management System (NMS) or through a performance monitoring system. The PLID maintains up-to-date information on any possible PLI concerning any network link. Whenever a new connection request arrives to a node, it sends a query to the PCE. The PCE computes the required path taking into account the TED and PLID information and sends back the computed explicit route to the source control module. The source node, using the standard signalling protocol (PATH/RESV messages), establishes the lightpath.

Slightly different approaches are followed in [TMK+08], [LTG+08]. In [TMK+08] PCE interworks only with NMS. In such a case, the NMS is in charge of collecting the connection requests, send them to the PCE together with all required information such as PLI performance, topology and logical link status, and get the computed routes. Afterwards, NMS sends the routes to the nodes which establish the lightpaths using the standard signalling protocol.

In [LTG+08], the authors propose an OPM manager, which is directly integrated in the NMS instead of a separate PCE, but the behaviour and functionalities are similar to the PCE model.

2.6.2 Routing-based Approach

The routing based approach, as depicted in Figure 2-4(b) has been mentioned in [SCT01] and consists of extending the routing protocol (as e.g., the OSPF-TE in GMPLS CP) to involve the PLI constraints into the IA-RWA problem. As described in [MPC+06], each node is in charge of storing updated TED and PLID databases on the resource utilization and on the PLI performance concerning any link in the network. As in the case of the TE attributes, local PLI (i.e., PLI performance of local node and of the attached links) can be included in the PLID using local monitoring while remote PLI can be obtained by exploiting the extended routing protocol. Whenever a new connection request arrives to a node, an on-line IA-RWA algorithm computes the route taking into account the TED and PLID information. Once the path is computed, the node activates the standard signalling protocol to establish the lightpath.

A different routing model is considered in [SYZ2+07], where no routing protocol extensions are required. Global wavelength availability is stored in the TED of the nodes and updated by the standard routing protocol while the PLID is not necessary. Indeed, only PLI constraints of static nature or function of the number of active wavelengths are considered and their mathematical models are preloaded into the control module of the nodes. Any incoming connection request triggers therefore the IA-RWA algorithm that computes a set of candidate routes according to the TED information and checks its feasibility by means of the mathematical models. If at least one feasible computed route exists, a lightpath is then established by the signalling protocol.

2.6.3 Signalling-based Approach

The signalling based approach (Figure 2-4(c)) has been proposed in [CAV$^+$04] and consists in extending the signalling protocol (as e.g., RSVP-TE in GMPLS CP) to encompass the PLI constraints. In such a model no modifications are introduced in the routing protocol [SYZ^{2+}07], [CAV+05]. Whenever a connection request arrives to a node, it computes a route according to the TED information and launches a setup request message in the network. This message collects estimated PLI performance of any traversed link between source and destination node. In fact, each node must store updated local PLID and mathematical models to calculate the PLI performance. If the accumulated PLI performance on the receiver interface at the destination node is compliant with an acceptable signal quality, a positive response message is sent back to the source node and the lightpath is established. If the accumulated PLI performance is not satisfactory, an error message is sent back to the source node and another attempt can be triggered following different route.

In order to decrease the delay of the lightpath establishment process, some improvements are described in [SYZ$^+$07], and [SGA$^+$06]. In [SYZ$^+$07], four different approaches are proposed and compared: in K-seq, the source node computes *k* different routes and sequentially attempts to establish a feasible lightpath; in K-par, the source node sends simultaneously *k* setup messages and the destination node can pick one according to some criteria and generates the response message; in HbH, the route is computed hop-by-hop, which means that each node takes into account only the information on the adjacent links; in FF, the setup message is flooded to the entire network. In [SGA$^+$06] the Lightpath Provisioning with Signalling Feedback (LPSF) concept is defined. It exploits the error message delivered to the source node adding some feedback information on the PLI performance of the rejected route. The source node can therefore store this information in the local PLID and compute additional feasible routes.

2.6.4 Comparison and discussion

Being a centralized approach, the PCE model is able to provide optimal path computation in terms of both network utilization and optical signal quality. It also does not require any modification or extension to the current signalling and routing protocols. At the same time, PCE has a global view of the network and, if there is no inconsistency in the databases, the setup procedure does not require any re-attempt, which can speed up the service provisioning. Nonetheless, it suffers from scalability problems and in case of failure rapid restoration cannot be achieved. There are some reasons to consider the PCE model for multi-domain scenario, where an abstraction of the entire routing area may optimize the inter-domain paths [MPC$^+$06], [CPV$^+$07].

Maintaining accurate routing information on all network nodes under dynamic traffic is extremely difficult. Therefore, routing model seems less advantageous solution since in addition to the TED information it requires the global dissemination of the PLI performance data. It may give some benefits in case of static traffic, or less volatile traffic conditions, but in such a case the PCE model may outperforms the routing one.

The signalling model seems to be the easiest and fastest way to encompass the PLI performance into the RWA problem. On the other hand, it is not able to provide optimal resource utilization and signal quality. It may require high setup delay due to the re-attempts of failed lightpath establishment processes.

Table 2-6: Requirements, pros and cons of the PCE model, routing model and signalling model

Model	References	Approach	Requirements	Pros	Cons
PCE	[MPC$^+$06], [CCV$^+$07], [CPV$^+$07], [TMK$^+$08], [LTG$^+$08]	Centralized	PCE with high reliability; Global TED and PLID databases	Global network view; Optimal path computation, signal quality and network resource utilization; No changes in control protocols; Useful for multi-domain scenario	Low flexibility and scalability; Vulnerability to database failure; Slow recovery; Depend on OPM; Intensive computation
Routing	[SC05], [SCT01], [SYZ^{2+}07], [MPC$^+$06]	Distributed	Global PLID database; Some extensions to disseminate efficiently the PLI performance	Distributed approach like Internet philosophy; Optimal path computation; Fast setup delay	Slow convergence; Intensive computation; Depend on OPM
Signalling	[SYZ$^+$07], [CAV$^+$04], [SYZ^{2+}07], [MPC$^+$06], [CCV$^+$07], [CAV$^+$05], [SGA$^+$06]	Distributed	Local PLID database; Mathematical models for PLI estimation; Some extensions	Distributed approach like Internet philosophy; Minor changes in signalling protocol; No dissemination overhead	High setup delay; Signalling overhead; No optimal resource utilization; No optimal signal quality

2.7 Discussions

In the previous sections of this chapter some of the most relevant works in the literature related to the planning and operation of optical networks (specifically IA-RWA algorithms) were reported and overviewed and the required modification to the control planes. However there are still some points which are either not reported in the literature or few works are devoted to them.

Multicast routing in wavelength switched optical networks has received some interest recently. Data duplication is performed in the optical domain at a set of branching nodes by splitting the optical signal using passive splitters. Considering multicasting in RWA problem is also NP-complete like classical RWA [AD01]. Very few works addressed the multicast problem taking into account the physical layer impairments and, in particular, they only consider the power loss due to the passive splitters as a constraint [HK05], [XR04], [HK04], and [WWY01].

In general, the QoS support in physical impairment-aware optical networks has two folds. The first one corresponds to the physical layer performance and it refers to the pre-defined level of signal quality, as measured at the destination receiver, that allows for flawless network operation [DS05], [PBD$^+$06], and [MBA$^+$03]. Another interpretation of QoS can be found in [JF04]. There the authors introduce a model of network that is able to support differentiation of lightpath requests according to a set of routing constraints (such as e.g., max. transmission quality degradation, max. delay, or reliability).

Although the IA-RWA algorithms presented in the literature focus mainly on the optical circuit-switching (or wavelength-routed) networks, still there are issues specific to the optical burst/packet switching networks (OBS/OPS) that have to be addressed. To support short connection holding times it was proposed to incorporate the information about physical impairments into a setup control message, by means of a data vector that is processed at consecutive nodes [Gui06]. Another problem concerns OBS networks, where the transmission offset time may be affected by optical signal dispersion effects [Wil03].

Few works in the recent literature address the problem of regenerator and monitoring equipment (optical performance or impairment monitoring) placement and allocation. The regenerator placement is addressed in [EZK$^+$06], [PPK08], [PPK^{2}08], and [MBL$^+$08]. The allocation of regenerator is proposed in [CMS$^+$04], [YR05], and [JF04]. In [YR05], the Efficient Regeneration-Aware algorithm minimizes the number of used regenerators along the selected lightpath as well as the PLI constraints. In the DDWP (Distributed Discovery of Wavelengths Paths) method, [JF04], one of the objectives is the minimization of the utilization of electronic regeneration.

2.8 Chapter Summary

Routing and Wavelength Assignment is the core component in planning and operation of optical networks. Considering the physical layer impairments in the RWA decisions adds a new dimension to this problem. Heuristics, meta-heuristics and optimization techniques are proposed as algorithmic approaches to solve IA-RWA problems. The general approach to address the IA-RWA problem can be divided in two main categories. The first trend utilizes traditional RWA algorithms and after selecting the lightpath the physical constraints are verified; in this approach the IA-RWA algorithm is not deliberately designed for routing with PLI constraints. The second approach is to use some metrics, which are related to the PLI constraints as cost of the links in order to compute the shortest path(s). Assuming good algorithms are in place, a small number of wavelength conversions (either via OEO or all-optical conversion) is needed to approximate the performance of opaque network architectures. In addition to wavelength conversion via O-E-O conversion, grooming will become available in IA-RWA algorithms and network planning decisions in general.

The physical impairments and IA-RWA algorithms can be incorporated in control planes using PCE, routing and signalling model. The PCE model is able to provide optimal path computation in terms of both network utilization and optical signal quality. It also does not require any modification or extension to the current signalling and routing protocols. PCE has a global view of the network, which can speed up the service provisioning. Nonetheless, it suffers from scalability problems. Routing model seems less advantageous solution since in addition to the TED information it requires the global dissemination of the PLI performance data. The signalling model seems to be the easiest and fastest way to encompass the PLI performance into the RWA problem. On the other hand, it is not able to provide optimal resource utilization and signal quality. It may require high setup delay due to the re-attempts of failed lightpath establishment processes and possible sub-optimal route decisions due to impairment-unaware route computation.

There are quite few proposals that address the resilience and protection issues in the IA-RWA algorithms. In addition to simulation studies, experimental and some analytical models are available to evaluate the performance of the proposed algorithms. None of the surveyed works considers the inaccuracy of the physical impairment information (analytically computed or measured) into their IA-RWA algorithms. The proposed adaptive IA-RWA algorithms simply change their decisions assuming that the physical information are completely accurate.

Regenerator and/or monitoring equipment placement are important factors in the design phase of the network. By using a proper regenerator or monitoring equipment placement strategy in some nodes of the network, it is possible to obtain similar performance (in terms of blocking probability) of an opaque network with much lower cost. However, this topic is not enough investigated in the literature.

The overall conclusion is that IA-RWA algorithms play important roles in maximizing the performance of an optical network design. These algorithms, when exploited in transparent or translucent networks planning and operation tools, can provide similar utilization as an opaque architecture, but with lower cost.

Chapter 3:

3. Evaluating Quality of Transmission

Physical layer impairments accumulate as light propagates through a lightpath in the transparent optical networks. Therefore, it is possible to provision a lightpath, while its quality of transmission (QoT) does not meet the required threshold.

One of the key building blocks in an impairment aware planning and operation methodology for optical networks planning and design is a QoT estimator, which is typically a combination of theoretical models and/or interpolations of measurements, usually performed offline (in the lab, before the network is deployed), but also possibly online. A practical QoT estimator should be fast to ensure that lightpaths can be established in real time of course with proper accuracy. In this chapter, the important physical layer impairments, their classification into linear and nonlinear categories is presented. Then, various modelling approaches that have been reported so far to model the physical layer impairments and their impacts is reported. In order to evaluate the performance of the physical layer and in particular in order to evaluate the QoT of the lightpath for planning and operation of optical networks QoT estimator tool, which is named Q-Tool, will be presented. It will be utilized in impairment aware planning and operation modules. This tool (i.e., Q-Tool) is designed and developed in the framework of DICONET project (www.diconet.eu) and during the course of this Ph.D. study, two versions of Q-Tool is utilized inside the contributed algorithms. In this chapter, the functional blocks and internal details of these two Q-Tool versions are presented. The design and development of this tool is not a contribution of this Ph.D. study. However, this tool is extensively utilized as a QoT estimator building block in the contributed algorithms, and Network Planning and Operation Tool (NPOT) that are described in next chapters.

3.1 Physical Layer Impairments

As optical signals traverse the optical fibre links and propagate through passive and/or active optical components, they encounter many impairments that affect the signal intensity level, as well as its temporal, spectral and polarization properties. Physical layer impairments can be classified into linear and nonlinear effects. Linear impairments are independent of the signal power and affect each of the wavelengths (optical channels) individually, whereas nonlinear impairments affect not only each optical channel individually but they also cause disturbance and interference between them [FAT+02], [RDF+99].

Figure 3-1 depicts the classification of physical layer impairments, considering linear and non-liner categories. The physical layer impairments can be also classified to static or dynamic impairments, considering the dependence of impairments behaviour on external factors such as aging, temperature, and physical stress.

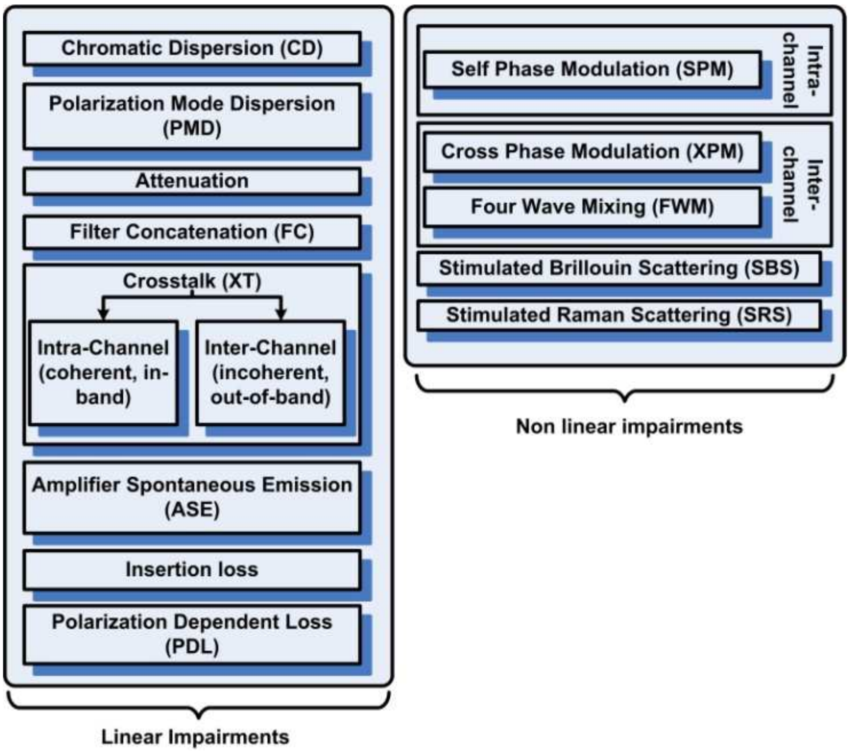

Figure 3-1: Classification of physical layer impairments.

Optical amplification in the form of Erbium Doped Fibre Amplifiers (EDFAs) always degrades the Optical Signal to Noise Ratio (OSNR). The amplifier noise is quantified by Noise Figure (NF) value, which is the ratio of the optical signal to noise ratio (OSNR) before the amplification to the same ratio after the amplification and is expressed in dB [FAT02].

Chromatic dispersion causes pulse broadening, which affects the receiver performance by: 1) reducing the pulse energy within the bit slot and 2) spreading the pulse energy beyond the allocated bit slot leading to inter-symbol interference (ISI). CD can be adequately (but not optimally) compensated for on a per link, and/or at transmission line design time [FAT02], [CCM05], [ZOG06], [SC05].

PMD is not an issue for most type of fibres at 10 Gbps, however it become an issue at 40 Gbps or higher rates [RDF+99], [SC05], [SCT01], [ZFG01], [MMH04]. In general, in combination with PMD there is also Polarization Dependent Loss (PDL). It can cause optical power variation, waveform distortion and signal-to-noise ratio fading.

Imperfect optical components (e.g., filters, demultiplexers, and switched) inevitably introduce some signal leakage either as inter-channel [FAT02], [SC05] (also incoherent [SC05] or out-of-band [PPK^{2}08]) or intra-channel [FAT02], [SC05] (or intraband [PPK^{2}08]) crosstalk in WDM transmission systems.

Filter concatenation is the last physical impairment that is considered and defined in this category. As more and more filtering components are concatenated along the lightpath, the effective pass band of the filters becomes narrower [SC05]. This concatenation also makes the transmission system susceptible to filter passband misalignment due to device imperfections, temperature variations and aging.

3.1.1 Linear Impairments

The important linear impairments are: fibre attenuation, component insertion loss, Amplifier Spontaneous Emission (ASE) noise, Chromatic Dispersion (CD) or Group Velocity Dispersion (GVD), Polarization Mode Dispersion (PMD), crosstalk (XT) (both inter- and intra-channel), and Filter Concatenation (FC). In the following subsections, the important linear impairments are briefly described.

3.1.1.1 Attenuation

Attenuation in fibre optics, also known as transmission loss, is the reduction in intensity of the light signal with respect to travelled distance through a transmission medium. The attenuation coefficient (α) in fibre optics is expressed in dB/km through the medium due to the relatively high quality of transparency of modern optical transmission media. The medium is usually a fibre of silica glass that confines the incident light beam to the inside. Attenuation is an important factor limiting the transmission of a digital signal across large distances. Empirical research has shown that attenuation in optical fibre is caused primarily by both scattering and absorption. When a signal with original power value of $P(0)$ propagates along the fibre for a distance of z km, its intensity becomes $P(z)$ as defined in the following formula:

$$P(z) = P(0)\exp^{-\alpha z} \qquad (2\text{-}1)$$

The attenuation depends on the wavelength. Figure 3-2 depicts the intrinsic losses due to the silica material. There are also additional reasons for this loss, such as the curvature radius, the fibre splicing, or the diameter changes of the fibre that contribute to the attenuation loss. The spectral window considered in telecommunication applications is centred around 1.55 μm mainly due to its relatively low loss (about 0.2 dB/km that is only 4.5%/km).

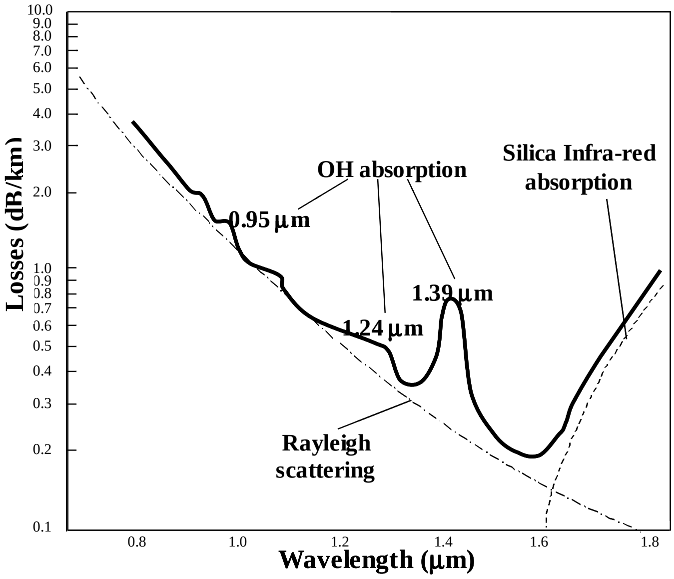

Figure 3-2: Light attenuation in fibre and loss vs. wavelength.

3.1.1.2 Amplifier Spontaneous Emission Noise

An optical amplifier is based on the stimulated emission. However this process goes with the spontaneous emission which adds incoherent photons to the amplified signal. Amplifier Spontaneous Emission (ASE) noise is always present when optical amplification takes place and can be classified among the most severe impairments in terms of limiting factors for optical reach and capacity. The ASE noise accumulates along the amplifiers chain. This accumulated ASE noise gives rise to signal-spontaneous beat noise at the receiver, which is the fundamental noise in an optically amplified transmission system.

The accumulated ASE power for a chain of N amplifiers is estimated using the following formula [Agr02]:

$$P_{ASE} = 2hvB_o n_{sp} N(G-1), \tag{2-2}$$

where P_{ASE} is the ASE noise power, B_o is optical bandwidth, h is Planck's constant, v is the optical frequency, n_{sp} is the spontaneous emission factor, and G is the optical amplifier gain. The spontaneous emission factor, n_{sp}, is determined by the inversion of Erbium ions. The contribution of each amplifier's ASE to the accumulated ASE is characterized by the amplifier's noise figure (NF), which at high gain can be approximated by $N_f \approx 2n_{sp}$. The coefficient of 2 in (2-2) accounts for the two orthogonal polarizations. One is parallel to the signal polarization and the other is orthogonal to it. The ASE noise variance at the end of the chain is described by [RDF$^+$99]:

$$\sigma_{ASE}^2 = 4R_\lambda^2 P_{i,avg}(N,\lambda)\frac{P_{ASE}(N,\lambda)}{2} B_e / B_o\,, \tag{2-3}$$

where $P_{i,avg}$ is the average power of the spaces (zeros) if $i = 0$ or the average power of the marks (ones) if $i = 1$, R_λ is the responsivity of the receiver, and B_e is the electrical bandwidth of the receiver. The average power of the signal takes into account the finite extinction ratio that is introduced into Q-Tool as a physical parameter of the transmitters (i.e., $P_{0,avg} \neq 0$).

3.1.1.3 Chromatic Dispersion

Chromatic Dispersion or Group Velocity Dispersion (GVD) is the phenomenon that causes different wavelengths of light to travel at different speed. This speed variation results to broadening of the optical pulses as they propagate through the fibre. The pulses then overlap, leading to Inter-Symbol Interference (ISI) and higher bit error rate. In general, the chromatic-dispersion limits the maximum transmission distance by decreasing it rapidly in inverse proportion to the square of the bit rate. For instance, systems running at 2.5 Gbps can cover distances of 940 Km with only a 1-dB power penalty due to chromatic dispersion, whereas at 10 and 40 Gbps, the distance shrinks to only 60 and 4 Km respectively.

The speed of a light wave is dependent on the refractive index of the medium within which it is propagating. In silica fibre, as well as many other materials, the refractive index varies with wavelength. Therefore, different wavelength channels will travel at slightly different speeds within the fibre. Laser sources are spectrally thin, but not monochromatic. This means that the input pulse contains several wavelength components, travelling at different speeds, causing the pulse to spread. The detrimental effects of chromatic dispersion result in the slower wavelengths of one pulse intermixing with the faster wavelengths of an adjacent pulse, causing inter-symbol interference (ISI) (Figure 3-3).

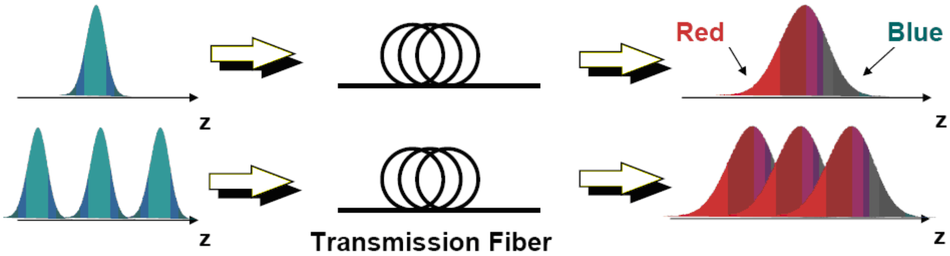

Figure 3-3: Optical pulse spreading due to chromatic dispersion.

Chromatic dispersion occurs mainly due to two reasons: 1) The dependence of the optical fibre's index on the optical wavelength and 2) The waveguide dispersion, where the power distribution of a mode between the core and the cladding of the fibre is a function of the wavelength.

The practical and mature technique to compensate for chromatic dispersion is by using dispersion-compensating fibres (DCFs) that have a dispersion characteristic that negates (i.e., compensates) that of the original transmission fibre. However, DCFs are expensive and bulky; for every 80-100 Km of SSMF, several kilometres of DCF are required.

3.1.1.4 Polarization Mode Dispersion

Light travelling along a single mode fibre has a pair of polarization modes that move toward the receiver at right angles to each other. Since the core of the fibre is not perfectly symmetrical, travelling light along the two polarization axes moves at slightly different speeds. Fibre-based Polarization Mode Dispersion (PMD) arises in an optical fibre due to asymmetries in the fibre core that induce a small amount of birefringence that randomly varies along the length of the fibre. This birefringence causes the power in each optical pulse to split between the two polarization modes of the fibre and travel at different speeds, creating a Differential Group Delay (DGD) between the two modes that result in pulse spreading. After a sufficiently long distance, this effect can change the shape of the pulses so that interference between pulses occurs [RS02]. Let D_{PMD} denotes the PMD parameter associated with a given fibre. Typical value of this parameter is in the range of 0.1 to 2.0 and its dimension is $ps/\sqrt{km}$. Active PMD compensation can be carried out using either electrical or optical techniques. The electrical approaches apply electrical filters to the received data signal, which can remove some of the PMD-induced distortions [WCK⁺01]. In the optical domain, the PMD-induced distortion is compensated by applying birefringent DGD-equalizers that can more or less reproduce the fibre behaviour with the opposite sign of D_{PMD} .

The impact of attenuation, chromatic dispersion and polarization mode dispersion (the ISI impact) is depicted in Figure 3-4. The impact of this impairments are properly considered and modelled in the QoT performance evaluator (i.e., Q-Tool).

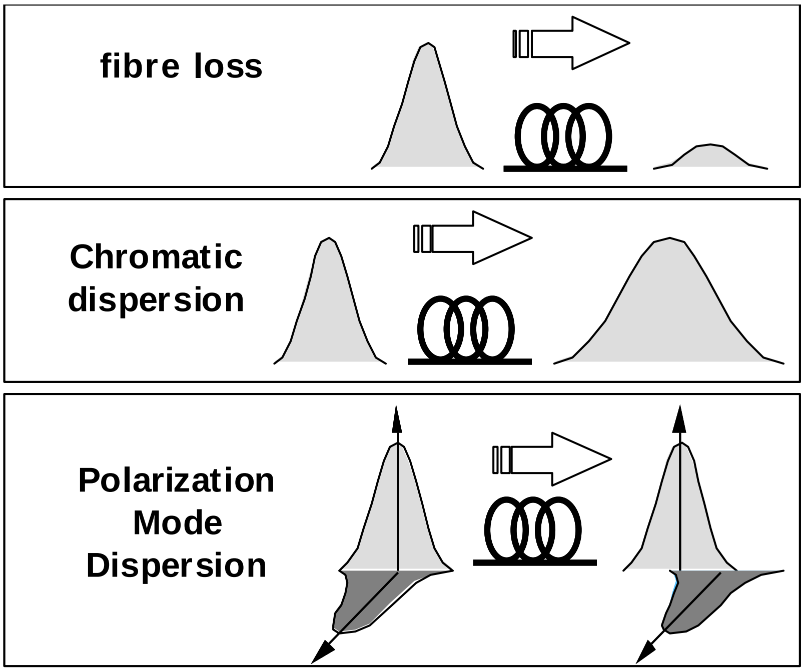

Figure 3-4: The ISI impacts (Fibre loss, CD and PMD).

3.1.1.5 Filter Concatenation

In optical networks, the optical signal passes through a number of concatenated components, such as WDM multiplexers (MUXs), demultiplexers (DEMUXs) and noise limiting optical bandpass filters, all of which can serve as optical filters. The concatenation of optical filters makes the system susceptible to filter passband misalignments arising from device imperfections, temperature variations and aging. The emission spectrum of the laser source may also be misaligned with the effective centre frequency of the optical filters due to manufacturing tolerances, aging, or operating conditions. Performance degradation in WDM systems may arise due to the combined effects of optical filter misalignments, laser misalignments, and laser chirp. The effects of filter concatenation are generally not a concern in a point-to-point optical system, in which a given signal passes through, at most, two filters (a multiplexer and a demultiplexer). However, in a transparent optical network, a signal may be de-multiplexed and re-multiplexed at many optical cross-connects or optical add-drop elements throughout its path before it is finally received at the destination node. Thus, the signal experiences the concatenation of the entire set of filters in its path.

The effective spectral transfer function of the cascaded filter set is the multiplication of each of the individual filters, which can, therefore, be much narrower in spectral width than a single filter. Spectral narrowing of the effective transfer function can be further exacerbated by any misalignments in centre frequency of the individual filters traversed by the signal. If the transmission laser frequency has an offset from the centre of the passband of the effective filter transfer function, then part of the signal spectrum may be attenuated as it gets too close to one of the sidewalls of the filter transfer function. This, in turn, can lead to a time-domain distortion and a distortion-induced eye-closure penalty in addition to simple excessive signal loss. Therefore, the overall Filter Concatenation (FC) degradation is taken into account by estimating the eye closure penalty that introduces at the receiver node.

3.1.2 Non-linear impairments

Important non-linear impairments can be summarized as Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Four Wave Mixing (FWM) [MMK08], Stimulated Brillouin Scattering (SBS), and Stimulated Raman Scattering (SRS) [Agr01].

The nonlinear phase shift manifests as phase modulation. In SPM the phase of the signal is modulated by its own intensity; while in XPM the signal phase is modulated by the intensity of other signals [FAT02]. The primary effect of these impairments is pulse broadening in frequency domain without changing the shape of the signal. The four-wave mixing nonlinear interaction in an optical fibre is originated from a weak dependence of the fibre refractive index on the intensity of the optical wave propagating along the fibre.

SBS and SRS involve non-elastic scattering mechanism [FAT02], [Agr01]. These impairments set an upper limit on the amount of optical power that can be launched into an optical link. In the following sub-sections each of these impairments are briefly described.

3.1.2.1 Self Phase Modulation

Self Phase Modulation (SPM) arises because the refractive index of the fibre has an intensity dependent component. This nonlinear refractive index causes an induced phase shift that is proportional to the intensity of the pulse. Thus different parts of the pulse undergo different phase shifts, which give rise to chirping of the pulses. Pulse chirping in turn enhances the pulse-broadening effects of chromatic dispersion. This chirping effect is proportional to the transmitted signal power so that SPM effects are more pronounced in systems using high transmission powers. The SPM-induced chirp affects the pulse-broadening effects of chromatic dispersion and thus is important to consider for high-bit-rate systems that already have significant chromatic dispersion limitations. For systems operating at 10 Gbps and beyond, or for lower-bit-rate systems that use high transmission power, SPM can significantly increase the pulse-broadening effect.

The combined effect of dispersion and SPM strongly depends on the sign of dispersion parameter. In terms of the sign of dispersion, the operating wavelength region is divided into two regimes: normal dispersion and anomalous dispersion regimes. The normal dispersion regime corresponds to the wavelength range in which dispersion parameter (D) is negative whereas the anomalous dispersion regime is the wavelength region in which D is positive. In particular, the SPM enhances the effect of dispersion when the operating wavelength is in the normal dispersion regime.

3.1.2.2 Cross Phase Modulation

Similar to the SPM, cross-phase modulation (XPM) is due to the nonlinear behaviour of the refractive index, which depends on the optical intensity. The refractive index of an optical field inside an optical fibre depends not only on the intensity of that field but also on the intensity of other co propagating fields. In this case, the total nonlinear phase shift on a given channel is due to the combined intensities of all transmitted channels, which can result in crosstalk among WDM channels.

When pulses at different wavelengths are considered, the effect of XPM depends on the relative temporal locations of those pulses. The strongest XPM effect occurs, when pulses completely overlap each other. However, the probability that all channels simultaneously transmit a “1” bit is low. Therefore, the impact of XPM impairment is reduced on average. Dispersion makes pulses at different wavelengths travel at different group velocities, which in effect causes pulses to walk off from each other. Hence, the impact of XPM is decreased. The larger the dispersion discrepancies among channels, the more rapidly the pulses walk off from each other. In other words, the effect of XPM is inversely proportional to the dispersion discrepancies among channels. Therefore, in order to minimize the impact of XMP, the channel separation and/or local dispersion have to be properly applied in WDM systems.

3.1.2.3 Four Wave Mixing

The four-wave mixing (FWM) nonlinear interaction in an optical fibre is originated from a weak dependence of the fibre refractive index on the intensity of the optical wave propagating along the fibre. Four-wave mixing is third-order nonlinearity in silica fibres, which is analogous to intermodulation distortion in electrical systems. The intensity dependence of refractive index not only causes nonlinear phase shift but also gives rise to the process by which signals at different wavelengths are mixed together producing new signals at new wavelengths. The difference between the processes causing the nonlinear phase shift (i.e., SPM and XPM) and the FWM process is that in FWM process energy transfer occurs. Moreover, the FWM effect is independent of the bit rate, but is critically dependent on the channel spacing and fibre chromatic dispersion. Decreasing the channel spacing increases the four-wave mixing effect, and so does decreasing the chromatic dispersion. When signals at frequencies f_i, f_j and f_k propagate along an optical fibre, the nonlinear interactions among those signals by mean of FWM result in the generation of new signals at [Agr01]:

$$f_{ijk} = f_i + f_j - f_k \, . \tag{2-4}$$

Thus, three co-propagating waves give rise to new optical waves due to FWM. In a WDM system, this happens for every possible choice of three channels, therefore, even if the system has only ten channels, hundreds of new components are generated due to FWM impairment.

In WDM systems with equally spaced channels all the product terms generated by FWM fall in the channel frequencies and giving rise to crosstalk. There are two techniques to mitigate this impairment: 1) Unequal spacing of the channel frequencies and 2) Dispersion management of the fibre.

3.1.2.4 Stimulated Raman Scattering

Scattering is a fundamental loss mechanism in optical fibres. Scattering can be classified into two major categories, which are the elastic and inelastic scattering. In elastic scattering the frequency (or the photon energy) of scattered light remains unchanged, whereas in inelastic scattering the frequency of scattered light is shifted downward. Two examples of inelastic scattering are Raman Scattering and Brillouin Scattering. The main difference between them is that optical phonons participate in Raman scattering, whereas acoustic phonons participate in Brilouin scattering. Both scattering processes result in a loss of power at the incident frequency.

The effect of SRS is not very severe in typical situations. The probability that all channels simultaneously transmit a “1” bit is inversely proportional to the number of channels. The effect of SRS is also reduced due to dispersion effect. Fibre dispersion causes the signals at different wavelengths to travel at different speeds, causing walk-off between bit sequences at different channels. The walk-offs among channels decreases the effect of SRS, hence increasing the tolerable threshold power. In general, SRS is not the limiting factor in lightwave communication systems compared with the other nonlinear effects.

3.1.2.5 Stimulated Brillouin Scattering

This nonlinear effect is due to the interaction between the incident light and acoustic vibration in the optical fibre. Similar to SRS, stimulated Brillouin scattering (SBS) causes frequency down-conversion of the incident light, but the frequency shift in this case is equal to the frequency of the interacting acoustic wave. However, unlike Raman-scattered light, the Brillouin-scattered light propagates in the backward direction. These causes excess loss on the incident light similar to SRS.

Once the power launched into an optical fibre exceeds the threshold level, most of the light is reflected backward through SBS. Due to its low threshold value, SBS limits the launched power to a few mill watts [Agr02].

SBS phenomenon introduces a limiting factor on the transmission launch power. However, the SBS threshold can be increased through broadening the effective line width of the signal, which can be achieved by frequency dithering, duobinary modulation, phase modulation or the phase modulation effect induced by the cross-phase modulation between WDM signals [LLS$^+$01] .

3.2 Physical Layer Impairments Models

In order to incorporate the physical layer impairments effects in the network planning and operation phases (e.g., IA-RWA algorithms) two general models have been reported in the literature. These approaches are: 1) analytical models, 2) Hybrid (analytical models accompanied by simulation results or optical impairment monitoring techniques). In the former the physical layer impairments are evaluated using closed-form formula and in the latter some simulation results or real-time impairment monitoring are also considered for the evaluation of the physical layer performance. Among a number of measurable optical transmission quality attributes (e.g., optical power, OSNR, CD, PMD, Q-factor (e.g., [PPK08], [KTM^{+}05], [MST^{+}07]) shows the best suitability as an integrated metric for routing algorithm, due to its close correlation with BER. Q-factor is sensitive to all forms of BER affecting impairments.

It is also possible to evaluate the quality of transmission using hybrid or experimental-based models. Authors of [MBL^{+}08] report the Quality of Transmission (QoT) function. This function is obtained by considering experimental measurements. Authors of [EZK^{+}06] have also used a similar function. Table 3-1 summarizes the reported performance evaluation techniques along with the relevant references.

Table 3-1: Performance evaluation techniques for physical layer impairments

Performance Evaluation Technique	References
Analytical models	
Linear impairments	[RDF^{+}99], [ZOG06], [MMH04], [JF02], [PBS07], [SYZ^{+}07], [MSM^{+}07], [HHM05], [CMS^{+}04], [MBA^{+}03], [YSR05], [ZPS^{+}07], [YR05], [ZNC07], [HBS^{3}07], [HK05], [CAV^{+}04], [TVM+04], [JF04], [SYZ^{2+}07], [PW06], [PZW+08], [MPC^{+}06], [TMK^{+}08], [LTG^{+}08], [CAV^{+}05], [SGA^{+}06]
Non-Linear (and linear) impairments	[MMK08], [PCB^{+}07], [ZPS^{2+}07], [PB06], [HBP^{2+}07], [HBP^{+}07], [MST^{2+}07], [PBD^{+}06]
Hybrid approach	
Analytical and simulation (linear and/or non-linear impairments)	[PPK08], [CCM05], [PPK^{2}08], [CMS^{+}04], [CCM06], [KTM^{+}05], [MST^{+}07]
Analytical and Monitoring/Experiments (linear and/or non-linear impairments)	[EZK^{+}06], [MBL^{+}08], [LTG^{+}08]

Some physical impairments have strong dependency on bit rates, modulation formats and type of amplifier that are considered as part of the optical links model. Table 3-2 summarizes different modulation formats, type of optical amplifiers and also bit rates that are assumed and reported in surveyed studies.

Table 3-2: Considered modulation format, amplifiers, and bit rates

Modulation		Amplifier Type		Bit rate		
OOK (NRZ/RZ)	DQPSK	EDFA	RAMAN	<10G	10G	40G (and 10G)
[PPk08], [ZOG06], [PPK^{2}08], [MBL^{+}08], [PB06], [HBP^{2+}07], [HBP^{+}07], [HBS3-07], [TVM^{+}04], [PBD^{+}06]	[LTG^{+}08]	[PPK08], [RDF^{+}99], [PPK^{2}08], [JF02], [SYZ^{+}07], [CMS^{+}04], [MBA^{+}03], [YSR05], [CCM06], [PB06], [KTM^{+}05], [YR05], [MST^{+}07], [ZNC07], [HBP^{2+}07], [HBS^{3}07], [MST^{2+}07], [TVM^{+}04], [SYZ^{2+}07], [PW06], [PZW^{+}08], [PBD^{+}06], [MPC^{+}06], [LTG^{+}08],	[HHM05]	[RDF^{+}99], [CMS^{+}04], [YR05]	[PPK08], [CCM05], [PPK^{2}08], [MBL^{+}08], [SYZ^{+}07], [ZPS2+07], [CCM06], [PB06], [HBP^{+}07], [HBP^{2+}07], [MST^{2+}07], [PW06], [PZW^{+}08], [PBD^{+}06], [CCV^{+}07], [TMK^{+}08]	[PCB^{+}07], [HHM05], [TVM^{+}04], [LTG^{+}08]

As indicated in this table, there are few works in the state-of-the-art surveyed papers that consider the advanced modulation formats and Raman amplifiers in their studies. Also higher bit rates and the challenges that they will introduce are areas that require more research.

In addition to analytical and simulation techniques for modelling physical layer impairments, monitoring techniques are required for measurements, which potentially can enhance the PLI-RWA algorithms. The monitoring could be implemented on the impairment level (Optical Impairment Monitoring - OIM) or at the aggregate level where the overall performance is monitored (Optical Performance Monitoring – OPM) [KBB+04], [Wil06].

3.3 QoT Estimator

In the framework of DICONET project, the Q-Tool was developed to cover the need for an efficient QoT estimator that would evaluate the impact of the physical layer impairments on the signal quality (i.e., QoT). During the design and development of this tool, great effort was made to identify the dominant impairments, implement the physical layer models and integrate them into a single figure of merit, the Q-factor estimator. As mentioned before, this Ph.D. study utilizes this tool as a QoT estimator in its contributed planning and operation modules and algorithms. During the course of this study the Q-Tool was constantly updated and upgraded. Therefore, in this section two version of this tool: 1) Q-Tool version 2.21, which is used to evaluate the performance of the planning and operation mode algorithms (i.e., offline and online IA-RWA algorithms), and 2) Q-Tool version 3.33, which is integrated in the DICONET Network Planning and Operation Tool is presented. The core engines and design principle of these two tools are very similar and compatible with each other.

To estimate the QoT of a signal carried by a lightpath, the Q-Tool estimates a metric called "Q-factor" which is directly related to the Bit-Error Rate (BER) of a signal via the following relationship, in the case of on-off keying intensity modulated signals:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right). \tag{2-5}$$

The Q-factor is defined as [Agr02]:

$$Q = \frac{P_1 - P_0}{\sigma_1 + \sigma_0}, \tag{2-6}$$

where P_1 and P_0 are the means of the distributions of the received "0" and "1" symbols after photo detection, respectively, and σ_1 and σ_0 their standard deviations. The Q-Tool estimates the Q-factor of a lightpath based on the network topology and information about the physical network components. The Q-Tool incorporates the main impairments that affect signal propagation. In particular Q-Tool v2.21 accounts for the following impairments: Amplifier Spontaneous Emission (ASE) noise, filter concatenation, Polarization Mode Dispersion (PMD), Cross-Phase Modulation

(XPM), Four- Wave Mixing (FWM), and optical crosstalk originating from optical leaks within the optical cross connects.

Note that $P_0 \le P_1$ and following [NM02], the filter concatenation is actually modelled through a penalty on P_1, yielding a new quantity P_1^* that accounts for the eye closure incurred by filter concatenation. The PMD effect is modelled through a penalty on Q via a multiplicative factor η_{PMD} [Can03]. Hence, Q value computed by Q-Tool (ver. 2.21) is actually defined as:

$$Q_{est} = \frac{\eta_{PMD} P_1^*}{\sigma_1 + \sigma_0} . \tag{2-7}$$

In Q-Tool 2.21, ASE noise, node crosstalk, XPM and FWM are modelled through noise variances:

$$\sigma_1^2 = \sigma_{1,ASE}^2 + \sigma_{1,XT}^2 + \sigma_{XPM}^2 + \sigma_{FWM}^2 , \tag{2-8}$$

$$\sigma_0^2 = \sigma_{0,ASE}^2 + \sigma_{0,XT}^2 . \tag{2-9}$$

The contribution of XPM and FWM within σ_0 are negligible and Q-Tool v2.21 models these two effects via the variances σ_{XPM}^2 and σ_{FWM}^2 in (2-8) using the models developed in [Car99], [ZPB+96], [INO+94]. Crosstalk is modelled as in [RDF+99] within both σ_1 and σ_0 via $\sigma_{1,XT}^2$ and $\sigma_{1,XT}^2$, as is ASE noise via $\sigma_{1,ASE}^2$ and $\sigma_{0,ASE}^2$.

Although some effects depend solely on the network topology and physical parameters (ASE noise, PMD, filter concatenation), other effects (crosstalk, XPM, FMW) depend on the network state, that is, on which lightpaths are established in the network, thereby introducing QoT interdependence between the lightpaths established in the network.

The performance of the Q-Tool as a QoT estimator depends on the number of lightpaths that it should evaluate and also the number of channels that are available per fibre link. When the number of channels per fibre link and the number of lightpaths increase, the required time for Q-factor computation also increases exponentially. The performance of Q-Tool (version 2.21) is depicted in Figure 3-5. The network topology that is used for this performance evaluation is the DT Network as defined in Appendix A. The horizontal axis presents the number of active lightpaths in the network and the vertical axis presents the required time to compute the Q-factor of the all active lightpaths, when a new lightpath is going to be established in the network. It can be observed that by increasing the number of active lightpaths and also the number of channels per fibre links in the network, the required time is also increased exponentially.

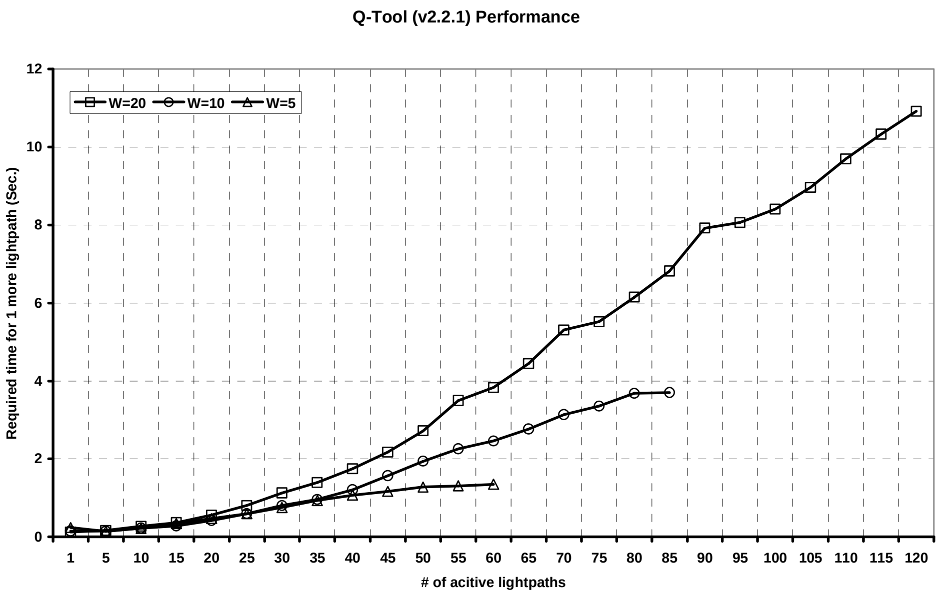

Figure 3-5: Performance of Q-Tool (ver. 2.21).

The Q-Tool (ver. 3.33) follows a slightly different approach to estimate the QoT of the lightpaths. The overall performance of the signal quality is reflected in the Q-factor, which combines the impact of key physical impairments in a single figure of merit (Q_{est}) as follows:

$$Q_{est} = 20\log\left(\frac{I_{1,\min} - I_{0,Max}}{\sigma_{0,ASE} + \sqrt{\sigma_{1,ASE}^2 + \sigma_{XPM}^2 + \sigma_{FWM}^2}}\right) - Q_{penPMD} \qquad (2\text{-}10)$$

The term of $(I_{1,\min} - I_{0,Max})$ refers to the difference of the minimum detected current at the level of "1" and the maximum at the "0" level which defines the eye closure distortion induced by FC, SPM and CD on the signal. The denominator of the Q_{est} formula includes the variances of all the noise impairments that add up to the total signal power variance. $\sigma_{0,ASE}^2$ and $\sigma_{1,ASE}^2$ refer to the variance of the detected spaces and marks due to ASE noise. XPM and FWM are assumed only to add noise at the level of "1"s and therefore the non-linear induced degradation is expressed by σ_{XPM}^2 and σ_{FWM}^2. The PMD penalty on Q-factor is modelled using [Can03]:

$$Q_{penPMD} = 10.2 B^2 D_{PMD} L\,, \qquad (2\text{-}11)$$

where D_{PMD} is the fibre dispersion parameter, L is the length of the transmission fibre and B is the signal bit rate. Here Q_{penPMD} is the penalty to be deducted from the Q-factor (expressed in dB) that does not incorporate the PMD effects.

Since the Q-factor is in fact a figure of merit the PMD-induced penalty has to be subtracted from the total estimated Q-factor. Q-Tool computes the Q_{est} and offers fast assessment of the QoT of a signal given a specific list of lightpath(s), and physical topology specification using analytical and numerical simulations.

The Q-Tool considers the impact of XPM on the performance of a single link according to the Cartaxo analytical model [Car99], which is properly modified to match the specific link architecture. The analytical expression of σ^2_{XPM} is derived using the approach reported in [PRS$^+$06]. The model in [INO$^+$94] and [WW04] are used in Q-Tool to derive σ^2_{FWM} in a closed form.

The input of the Q-Tool is abstractly divided into two parts: the physical topology and a set of lightpaths. The physical topology is essentially the entire set of physical parameters that defines the network topology. The other input consists of the number of paths with their corresponding assigned wavelengths, which is usually the result of the Routing and Wavelength Assignment process that serves a given demand set (traffic matrix) or even a single demand. The Q-Tool then utilizes the physical layer models and information to estimate the impact of the physical layer impairments and their combined effect and return the Q-factor of each lightpath. The Q of each lightpath is merely a metric that characterizes its QoT.

Figure 3-6 depicts the main building blocks of Q-Tool. The Q-Tool core engine subsequently invokes the processes that evaluate the impact of the impairments and eventually combines all respective results to the Q-factor (i.e., Q_{est}). These processes account for the following physical layer impairments: Self Phase Modulation (SPM) with Chromatic Dispersion (CD), Filter Concatenation, Amplifier Spontaneous Emission (ASE) noise, Cross Phase Modulation (XPM), Four Wave Mixing (FWM) and Polarization Mode Dispersion (PMD).

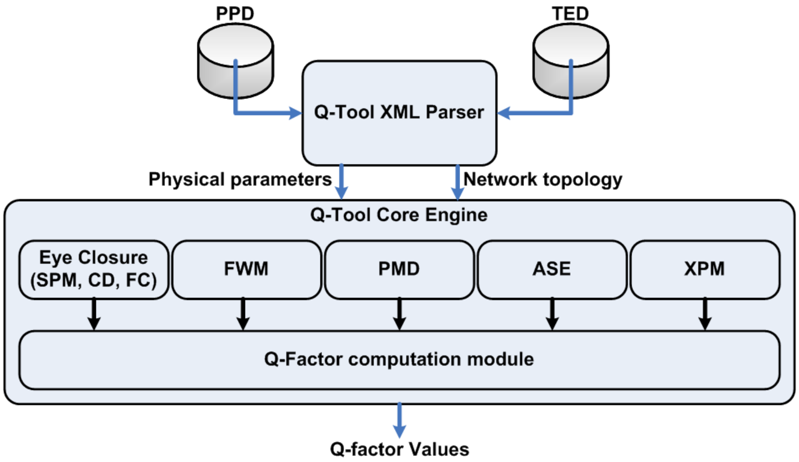

Figure 3-6: the key building blocks of Q-Tool.

The Q-tool estimates the Q-factor of a given lightpath in a two-step approach. First, single channel numerical simulations are performed to account for the deterministic distortions and then all the noise terms are calculated and added to the total Q value. The purpose for this selection was to have a combination of an accurate numerical method that applies only on a per channel basis, having therefore minimum effect in the processing time consumption, with a fast analytical estimation method that incorporates all additional distortions in the form of added noise.

3.4 Chapter Summary

As light propagates through a lightpath in the transparent optical networks, physical layer impairments accumulate on the transmitted signal. Therefore, it is possible to provision a lightpath, while its quality of transmission (QoT) does not meet the required threshold.

One of the key building blocks in an impairment aware planning and operation methodology for optical networks planning and design is a QoT estimator, which is typically a combination of theoretical models and/or interpolations of measurements, usually performed offline, but also possibly online. A practical QoT estimator should be fast to ensure that lightpaths can be established in real time of course with proper accuracy.

Physical layer impairments can be classified into linear (i.e., attenuation, CD, PMD, FX, crosstalk, ASE noise, insertion loss, and PDL) and nonlinear (i.e., SPM, XPM, FWM, SBS, SRS) effects. Analytical models (e.g., Q-Factor) or a hybrid approach considering analytical, simulation and experiments are proposed for modelling the physical impairments and incorporating their impacts in RWA algorithms. In addition to the detailed description of physical layer impairments, the findings regarding the physical layer impairments models are presented, which are reported in the state-of-the-art literature. There are few works in the state-of-the-art surveyed papers that consider the advanced modulation formats and Raman amplifiers in their studies. Also higher bit rates and the challenges that they will introduce are areas that require more research.

Finally, the QoT estimator that is utilized in this research introduced. The DICONET Q-Tool (both version 2.21 and 3.33) is a QoT estimator that considers the impact of key physical layer impairments and estimate the QoT of lightpaths, which is expressed in a single figure of merit (Q_{est}). This tool is not a contribution of this work; however it is extensively utilized in the contributed algorithms both for planning and operation of transparent optical networks.

Considering the complexity of a WDM system, the method that the Q-tool employs to estimate the impact of transmission impairments on the lightpath quality aims at a compromise between speed and accuracy in the manner described in this chapter.

Chapter 4:

4. Impairment-Aware Network Planning

The evolution of the optical networks as the main infrastructure underneath the emerging data-intensive applications is focused on the provisioning of more capacity in a cost effective manner. The evolution trend depicts a transformation towards higher capacity transparent optical networks with lower (CAPEX and OPEX) cost for the next generation core networks [BSB$^+$08], [STL08], [AKT$^+$09]. To materialize the vision of transparent optical networks, while offering efficient resource utilization and strict quality of service guarantees based on certain service level agreements, the core network should efficiently provide high capacity, fast and flexible provisioning of lightpaths, high-reliability, and integrated control and management functionalities.

During the planning phase, the traffic demand is already known at least partially, enabling the network operator to perform the resource allocation task offline. Since, in all-optical networks, bandwidth is allocated under the form of lightpaths (i.e., the combination of a route between two nodes, and a wavelength), the problem of pre-planned resource allocation in such networks is called static or offline Routing and Wavelength Assignment (RWA) problem [RS95], [ZJM00]. The other case, whereby traffic demands are assumed to arrive in a dynamic fashion, is referred to as the online or dynamic RWA problem.

In the second chapter (Chapter 2), a comprehensive literature review on the proposed algorithms that address the online and offline Impairments Aware Routing and Wavelength Assignment (IA-RWA) problem that account for physical layer impairments, was presented. Indeed it is now well-known that the impact of physical layer impairments on the QoT of the lightpaths without electrical regeneration can be reduced using appropriate IA-RWA algorithms [KTM$^+$05], and much research has been devoted to the online case. However, as indicated in Chapter 1 few works target the offline case compared with the proposed solutions for online IA-RWA problem; in addition, those proposed offline IA-RWA algorithms are evaluated for different metrics and network topologies, making them difficult to compare. Authors in [MCV09] present a Linear Programming (LP) relaxation formulation for RWA problem that tends to yield integer solutions. The signal degradation due to physical impairments is considered as additional soft constraints on RWA. The work in [MCK$^+$09] formulates the problem of regenerator placement and regenerator assignment in translucent optical networks, as a virtual topology design problem. Integer Linear Programming (ILP) and simple greedy heuristic algorithms are proposed to solve this problem. Once the sequence of regenerators to be used by the non-transparent connections has been determined, the initial demand set is transformed to a sequence of transparent connection requests that begin and terminate at the specified intermediate regeneration nodes. Then an IA-RWA algorithm is used to serve the converted demand set. Authors in [YSR05] address the issue of shared protection in translucent WDM mesh networks with consideration for physical layer impairments. None of these works tackle scenarios with dedicated protected demands. A recent study shows that the CAPEX difference of shared (e.g., 1:1) and dedicated (e.g., 1+1) path protection schemes is much lower in transparent optical networks comparing with its opaque counterpart [SCP+08], making dedicated protection attractive in transparent optical networks. For this reason, in this section, the problem of offline IA-RWA where some demands can require dedicated path protection is presented and tackled.

When it comes to protection and resiliency, the behaviour of all-optical components and architectures pose new challenges to the network designers. In cases where the efficient use of the network capacity is important and relatively slow restoration time in the order of hundred(s) of milliseconds is acceptable, shared protection schemes (e.g., 1:1) are applicable. In contrast, in dedicated protection (e.g., 1+1), both the primary (working) and the protection (backup) paths are active simultaneously, wasting resources but considerably decreases the restoration times (to less than 50 ms). A recent study shows that the difference in CAPEX between shared and dedicated path protection schemes is much lower in transparent optical networks than in opaque networks [SCP+08]. Since both the primary and the protection paths are established in dedicated path protection, there is no transient impact as in the 1:1 case, and thus a failure does not negatively affect the quality of established connections. This makes dedicated path protection a particularly attractive protection mechanism.

Few recent works consider the impact of physical layer impairments on dedicated path protection schemes. The authors in [JF04] propose an approach that considers both physical layer impairments and path reliability, in the form of a constraint-based path selection algorithm. In [ZPS07] the effect of physical layer impairments on dedicated path protection schemes is investigated. In the framework of all-optical networks with various path protection schemes, the authors of [ZPS+07] propose algorithms that exhibit low blocking probability without high computational complexity. These works consider a dynamic traffic scenario, where the lightpaths are established and are torn down on demand, in contrast to the static case which is the topic of this chapter.

In this chapter the impairment aware network planning problem in the context of transparent networks with dedicated path protection is investigated. The focus of this study is on dedicated path protection due to fast restoration, lower CAPEX and the absence of transient impairments phenomena, which occurs in non-dedicated protection approaches.

It is assumed that connection demands are known a-priori, given in a form of a demand set (traffic matrix Λ), and, in addition, demands with mixed levels of protection, e.g., some demands may require 1+1 protection while others require no protection at all are considered. A connection demand is defined as a 4-tuple $(s, d, p, \Lambda_{s,d})$, where s and d are the source and destination of the requested connection, p is the protection type (which can be a QoS feature), and Λ_{sd} is the number of wavelengths requested between nodes s and d. A given source-destination pair may require more than one wavelength ($\Lambda_{sd} > 1$) if the required data rate exceeds the channel capacity. Four levels of protection p are considered: The most basic level is p=1, which corresponds to connections that do not require any path protection. The most advanced level is p=4, which corresponds to connections that require the standard node-disjoint path protection (that is, the working and backup paths have to be node-disjoint). In addition, two intermediate protection levels are provided. With the “min nodes” (p=3) scheme, the proposed algorithm makes a best effort to find link-disjoint working and backup paths with a small number of common nodes. In the “min nodes and links” scheme (p=2) the number of common nodes and links is kept small. Note that these last two levels of protection are of the best-effort type, and no hard guarantees are given; they could be offered to customers as more flexible and cheaper alternatives to the full-fledge node-disjoint path protection scheme.

In general, the algorithmic approaches for the impairment aware network planning (also known as static IA-RWA problem) can be categorized as sequential approaches, based on some heuristic algorithm, or as combinatorial approaches, which search for an optimal solution. In this chapter a heuristic algorithm for the optical network planning (i.e., static or offline IA-RWA) problem is presented that accounts for the physical impairments and can also provide a variety of protection levels to connection demands. These protection levels range from dedicated node-disjoint protection paths to minimum common hops and link-disjoint paths. The proposed IA-RWA algorithm solves the offline traffic problem in a sequential manner. Initially, it orders the connections requests according to some criterion, and then proceeds to serve each connection request one by one. Since the order in which the demands are considered plays an important role in the performance of the algorithm, two ordering strategies are proposed and evaluated. The contributed algorithm is named **offline “Rahyab[1]”**. The offline Rahyab follows the sequential approach.

The contribution of Offline Rahyab, which is compiled in this Chapter, is four-fold. First, by design the offline Rahyab is a novel IA-RWA that natively accounts for dedicated path protection; second, a selected heuristic algorithm from the literature to better include QoT related impairments and to consider the dedicated path protection [EZK$^+$06] is presented and its performance is compared with offline Rahyab. Third, an ILP-based RWA formulation, from the state-of-the-art algorithms at the time of impairment aware planning study, is enhanced to include QoT requirements and also to incorporate protected demands [KTM$^+$05] and their performances under similar performance evaluation framework will be compared. The contributed novel heuristic algorithm performs better than the selected algorithms under the same assumptions. Finally, a potential usage of offline Rahyab as a re-routing strategy is demonstrated. Before describing the algorithm, its main building blocks is presented.

4.1 Building blocks of Offline Rahyab

In offline Rahyab lightpaths are established by considering the connection requests sequentially, in a defined order. To do this, an adaptive routing policy is proposed, where the selected path is dependent on the state of the network. Therefore, the order in which the demands are considered plays an important role in the

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1 - Rahyab means path finder in Persian language.

performance of the proposed algorithm. Hence, the first building block in our algorithm is a demand pre-processing module.

Two strategies to order the demands are proposed. The a-priori distance between two nodes *s* and *d* by the length of the shortest path between *s* and *d* is assessed. It is more difficult to accommodate calls between nodes that are far apart, because such paths use up more resources, hence the first approach is to order the demands based on the lengths of the shortest paths, where the longer paths are processed first. The second strategy accounts for the protection level demands, by considering another ordering criterion, in addition to the shortest path lengths. Thus, protected connections (node-disjoint protection or one of the two intermediate levels of protection) are routed earlier, as they require more resources and there is generally less flexibility in the way they can be routed. After protected connections have been served, the unprotected demands are routed next. Within each group (protected and unprotected), the demands are ordered by decreasing shortest path length. These two schemes are optionally combined with a round robin scheduling; when this strategy is applied, demands for Λ_{sd} >1 wavelengths are broken into Λ_{sd} demands for 1 wavelength, and these demands are served independently, with one wavelength being allocated at each round, in an order that is determined as above. This is illustrated in Figure 4-1 for a set of three demands. In short, two ordering schemes (longest shortest path first, and protection level then longest shortest path first) have been developed. Combining these two schemes with round robin ordering defines four different demand pre-processing policies (i.e., with or without round robin scheduling).

The routing engine utilizes the Breadth-First-Search Shortest path algorithm. This algorithm finds the shortest path, breaking ties by using the hop count as a secondary criterion. Note that increasing the size of the set of candidate paths has an adverse effect on the running time of the algorithm: as will be seen below, candidates are checked for QoT adequacy, and QoT computations are time-consuming. The size of the set of candidate paths can thus be seen as a tuning parameter for the trade-off between blocking probability and running time. Protection level is accounted for by this component as follows. If no protection is requested (*p*=1), a k-shortest path algorithm is used. If any kind of protection is requested (*p*=2, 3, 4), a modified Bhandari algorithm [Bha99], [Sim08] is run to find the primary and protection (backup) candidate paths.

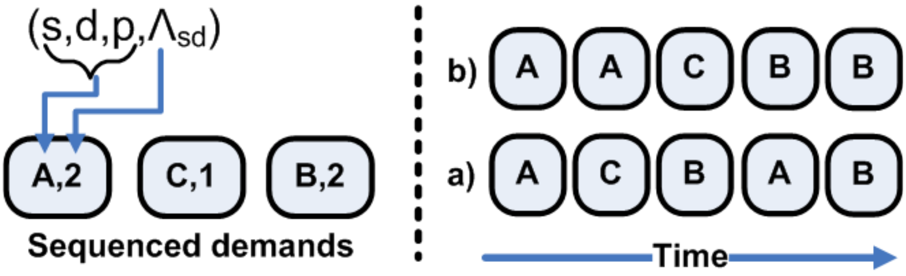


Figure 4-1: Processing order of demands a) with and b) without round robin scheduling.

This algorithm finds the pair of paths with the following objectives, tested sequentially: a) minimization of the number of common nodes, b) minimization of the number of common links (in case of a tie for objective (a)), c) minimization of the sum of the lengths of the two paths (if both (a) and (b) result in a tie). If this algorithm returns a pair of node-disjoint paths (objectives (a) and (b) were met with 0 common node and 0 common link), this pair is returned as the candidate pair irrelevant of the demanded level of protection (p=2, 3, 4). If the algorithm returns a pair with common nodes but no common link, and if the requested path protection is either minimum nodes and links, or minimum nodes (p=2, 3), then this pair is returned as the candidate pair. If the algorithm returns a pair with common nodes and common links, and if the requested path protection is minimum nodes and links (p=2), then this pair is returned as the candidate pair. Other cases result in a blocking.

Another key component in the contributed algorithm is the physical layer performance evaluator. The Quality of Transmission (QoT) of a lightpath is assessed through its Q-factor value using the Q-Tool (Version 2.21). This tool was defined in great detail in Chapter 3.

The last building block of proposed approach is a candidate selector: it selects the lightpath from the candidate routes and wavelengths according to the defined policy.

4.2 Offline Rahyab Algorithm

Using the building blocks introduced, the schematic flow of the proposed algorithm is depicted in Figure 4-2. Assuming an offline traffic scenario, the demands are known in advance. Protected and unprotected demands separately are treated. For unprotected demands a layered network graph (*LNG*) is constructed as follows. The network topology for a given WDM optical network is defined by a graph $G=(V,E)$, where V is the set of nodes in the network (vertexes), and E is the set of bidirectional links (edges) which in this case are optical fibres. Each link supports a set $C=\{1,2\ldots,W\}$ of wavelengths, and there are $W=|C|$ wavelengths available per link. A layered network graph $LNG=(V_W,E_W)$ is a directed graph constructed from G. Each node, $n \in V$, is replicated W times in the *LNG*. These replicas of n are denoted by $n(1), n(2),\ldots, n(W) \in V_W$. If link $l_{ij} \in E$ connects node n_i to node n_j, then nodes $n_i(w)$ and $n_j(w)$ of *LNG* are connected by links $l_{ij}(w)$ and $l_{ji}(w) \in E_W$ for all $w \in C$.

The representation of the *LNG* is shown in Figure 4-3. The diverse routing engine simply constructs a set of diverse routes in each wavelength layer of the *LNG* graph, which is similar to the “adaptive routing” [MA98] approach. In order to control the level of diversity of the routes, two parameters k and δ are defined, where k determines the number of computed shortest paths and δ defines the number of node and/or link disjoint diverse paths.

After constructing the pool of candidate paths, by utilizing the diverse routing engine, physical layer performance evaluator (that is the Q-Tool) is used to compute the impact of each candidate route on the currently established lightpaths. The impact of establishing the new lightpath is computed by subtracting a threshold from the Q-factor of all active lightpaths (including the candidate path) and finding the minimum value as expressed in:

$$Q_{Impact} = \min_{p,w}(Q_{p,w} - Q_{Threshold}), \qquad (3\text{-}1)$$

where $Q_{p,w}$ is the Q-factor of all active lightpaths (p,w).

The next step is to select a lightpath from the candidate lightpath list. A heuristic is considered, by which the candidate lightpath that yields a maximum Q_{Impact} value is selected. If this candidate lightpath is found then the lightpath will be established and the network topology graph will be updated to reflect the wavelength and route allocation. The intuition behind this is that since the network graph has been decomposed to different wavelength layers and for each layer a diverse set of candidate paths will be found, a lightpath with minimum QoT impact on the active lightpaths as far as the Q-factor metric is concerned, will be found.

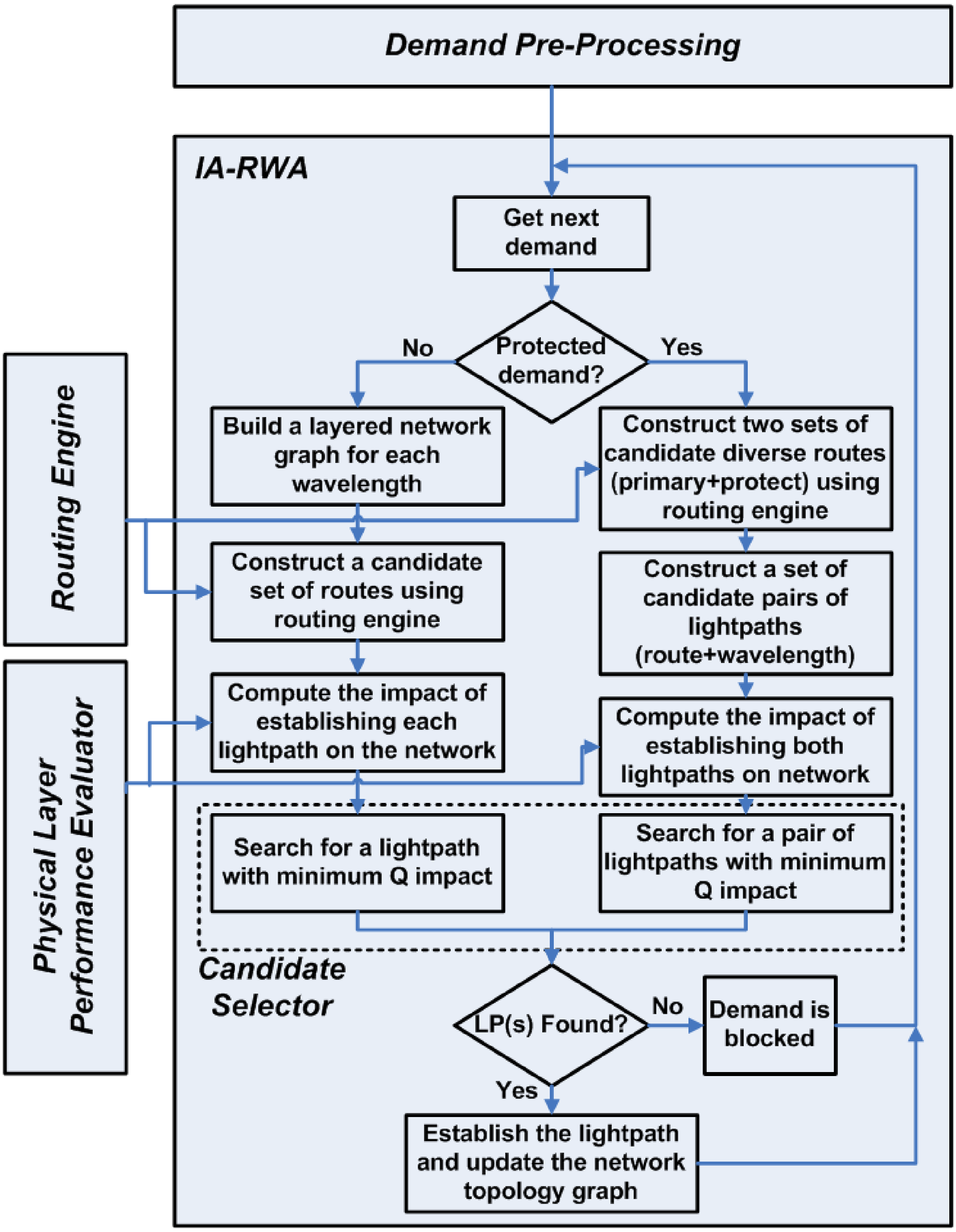


Figure 4-2: Building blocks and the flowchart of “Offline Rahyab” algorithm.

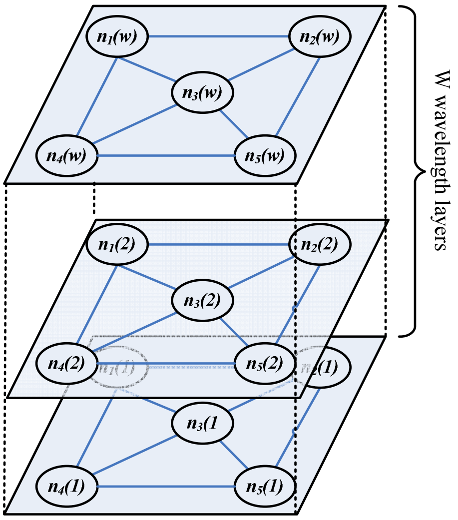


Figure 4-3: Layered network graph.

If the demand is requesting a protected lightpath (cases *p*=2, 3, 4), offline Rahyab algorithm constructs two sets of candidate paths. One set is for the primary lightpath and the other is for the protection (backup) lightpath. In 1+1 protection scheme, both lightpath will be established. Thus another set of lightpaths is constructed, which includes all possible combinations of primary and protection lightpaths. Note that all available wavelengths for each route are considered for each lightpath. The impact of lighting on both primary and protection path is then computed using the physical layer performance evaluator (i.e., Q-Tool). Eventually a pair is selected that introduces the minimum impact on the active lightpaths and the network graph will be updated accordingly. In both cases (i.e., unprotected or protected demands), if a proper lightpath or lightpaths pair is not found, then the demand is blocked. The performance of offline Rahyab algorithm (in terms of running time) highly depends on the performance of the physical layer performance evaluator.

4.3. Performance Evaluation of Offline Rahyab

A number of simulation experiments were performed in order to evaluate the performance of offline Rahyab algorithm. In order to evaluate the performance of the physical layer the Q-Tool (ver. 2.21) was used as a QoT estimator. The IA-RWA algorithm and routing engine were developed using OPNET Modeller simulation platform. The whole simulation scenario is conducted using a co-simulation approach between MATLAB and OPNET Modeller. The network topology in the simulation studies is the generic Deutsche Telekom national network (DT-Net) (Appendix A).

The line rate in this network is assumed to be 10Gbps. The traffic load in this network is defined as the ratio of the given number of connection requests over all possible connections.

Links are SSMF spans (3 dBm/channel, dispersion D=17 ps/nm/km, attenuation α=0.25~dB/km) with DCF (-4 dBm/channel, D=80 ps/nm/km, α =0.5 dB/km) under compensating the dispersion by 30 ps/nm/km in each span. A pre-dispersion compensator sets the initial dispersion to 400~ps/nm and a post-dispersion compensator sets the dispersion to 0 at the end of each link (before a node). Amplifiers compensate exactly for the losses incurred during transmission with a noise figure NF=6dB with small variations. The signal-to-crosstalk ratio was set around -32 dB with small variations in each node. The threshold value for computing the impact on Q-factor is 15.5dB (corresponding to BER=10^{-9} without FEC). The data rate is set to 10Gbps per wavelength in each network with a 50GHz channel spacing.

In Figure 4-5, the blocking rate for the DT network topology and 32 wavelengths per link is ploted. For the proposed algorithm *k*=10 shortest paths as candidate paths for each source-destination pair was used. A “pure RWA” algorithms, namely a typical impairment-unaware RWA (IUA-RWA), where the shortest path over the whole set of candidates is chosen, is compared with the proposed IA-RWA algorithm. In the pure-RWA algorithm case, the lightpaths that do not meet the QoT constraint are blocked after the algorithm has terminated. The flow chart of the impairment unaware RWA algorithm is depicted in Figure 4-4.

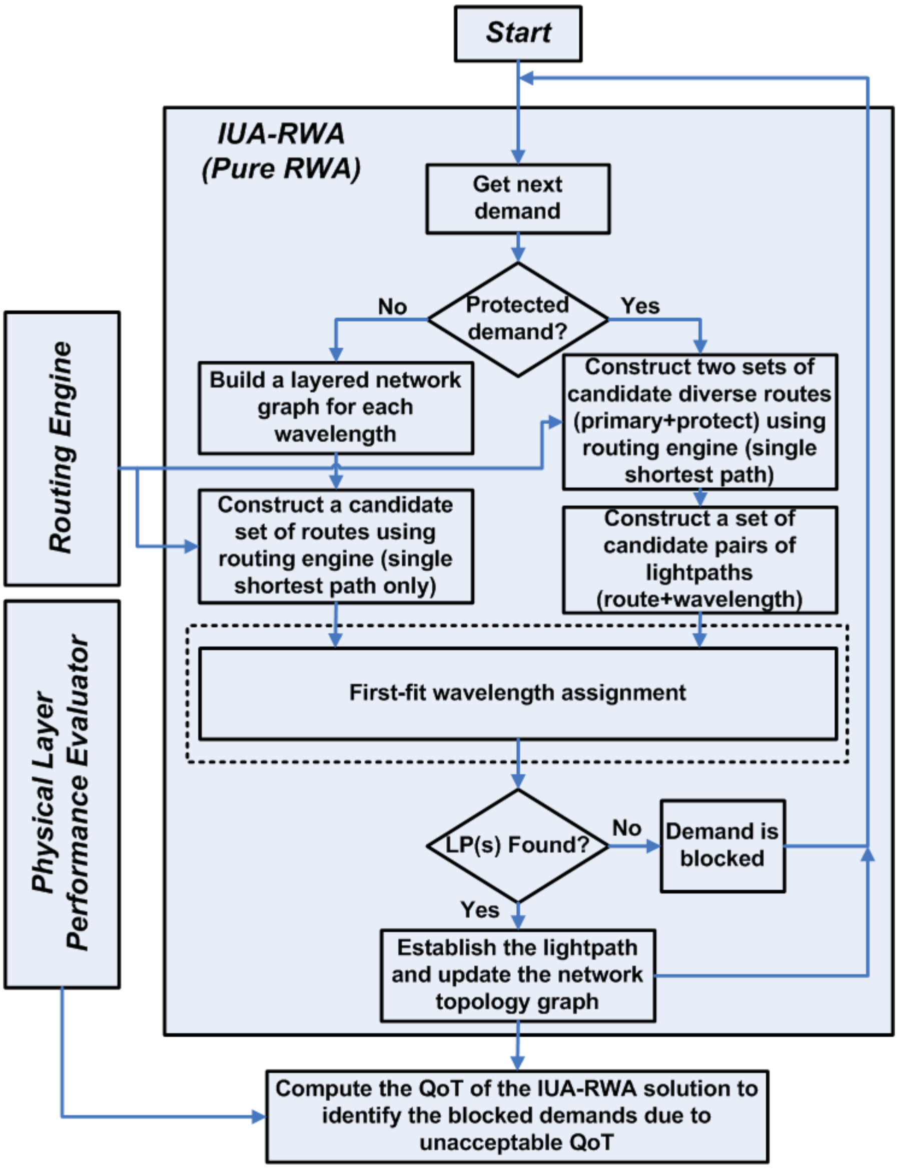


Figure 4-4: Flow chart of the Impairment unaware (Pure RWA) algorithm.

In addition, cases where *p*=0 (no protection for all demands) and cases where *p*>0 for 20% of the demands are separated. Proposed algorithms show a reduction of about 15-20% in blocking rate over the pure RWA algorithms. The gain is even higher for demands with protection, showing that proposed IA-RWA actually benefits best in (more realistic) scenario with protected demands. Very high reduction in blocking rates for each topology is achieved, showing the efficiency of offline Rahyab. In Figure 4-6 the same performance metric is depicted for EON network topology and various loads. The characteristics of the EON network is summarized in Appendix A. It is observed that for load=0.7, the gain of offline Rahyab is 35% better than IUA-RWA algorithm for un-protected demands.

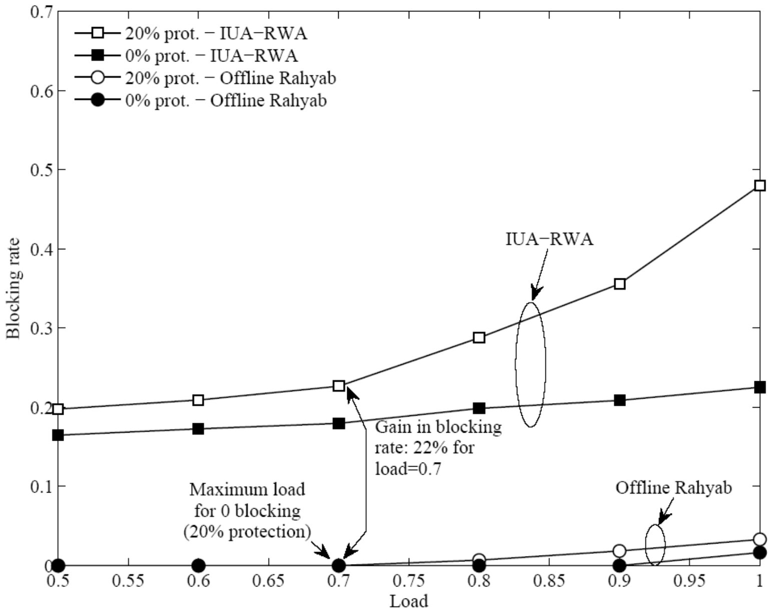


Figure 4-5: Blocking rate vs. traffic load (DTNet), assuming 32 wavelengths are available per link.

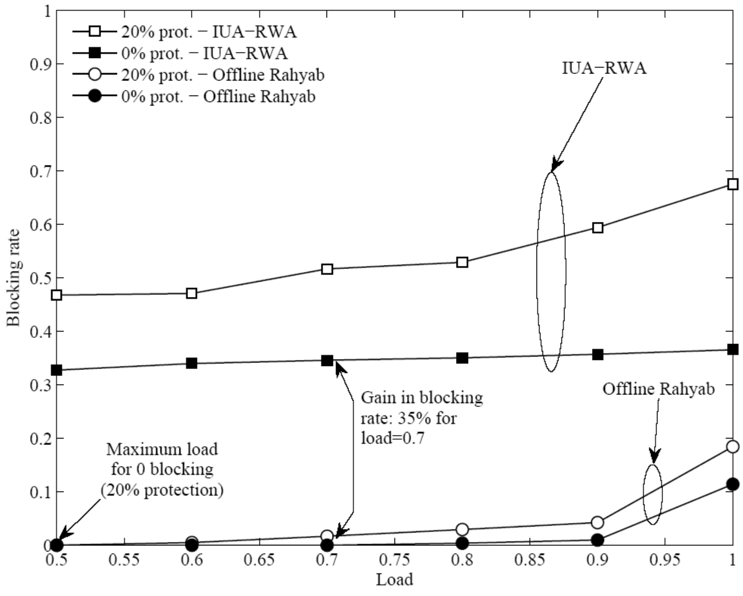


Figure 4-6: Blocking rate for EON network.

In Figure 4-7, the translation of this gain into resource requirements savings for the DTNet topology is shown. The maximum admissible load that results in zero blocking as a function of the number of wavelengths available per link is plotted. This data can be used by engineers to dimension the network at time it is designed, as it tells the amount of equipment needed (related to CAPEX) to run a network so as to serve all required connections. In particular, it can be seen that, for instance, for 16 wavelengths with 20% protected demands (*q*>0), the proposed IA-RWA can allow twice the load compared with the pure RWA. The results are similar when all demands are unprotected.

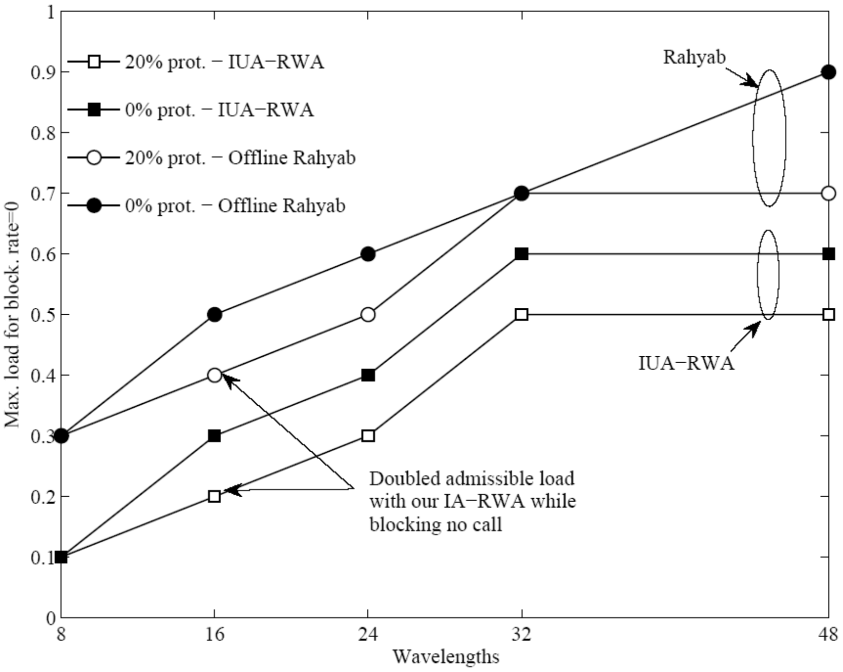


Figure 4-7: Maximum load that can be served with 0% blocking as a function of the number of available wavelengths.

In addition to EON and DTNet network topologies, the studies have been repeated using the Internet-2 network topology. The Internet-2 network has 9 nodes, 26 unidirectional links, and average node degree of 2.89 (as defined in Appendix A). The average shortest path length is 1266 km for Internet-2 topology. The traffic demand for Internet-2 is calculated based on a population-distance model. The traffic in Gbps between two nodes grows with the product of the population between both nodes, and decreases with the square of the distance between them. The base matrix is normalized; so that the sum of the offered traffic equals to 1 Tbps. These traffic matrix values are compiled in Appendix A. Note that all the traffic matrices are symmetric.

In Figure 4-8 the blocking rate versus the offered load corresponding to different demand sets is depicted. For the protected demand sets, it was assumed that 20% of the demands are requesting for a 1+1 dedicated protection. It can be observed that the performance of offline Rahyab is better than IUA-RWA algorithm for both protected and unprotected demands sets. The blocking rate of both algorithms for different value of available channels per link is depicted in Figure 4-9. It can be observed that for the experimented range of available channels per links, offline Rahyab performs better than IUA-RWA algorithm.

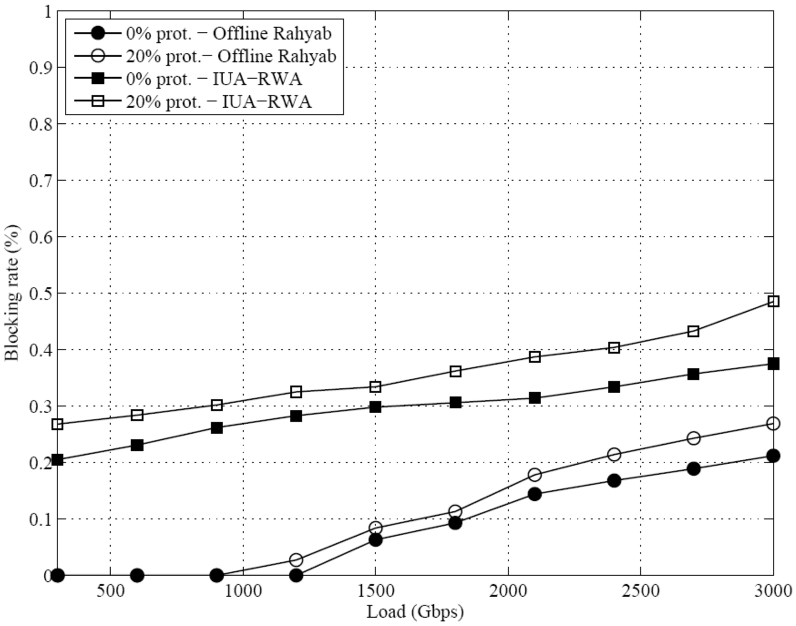


Figure 4-8: Blocking rate vs. load for Internet-2 network topology.

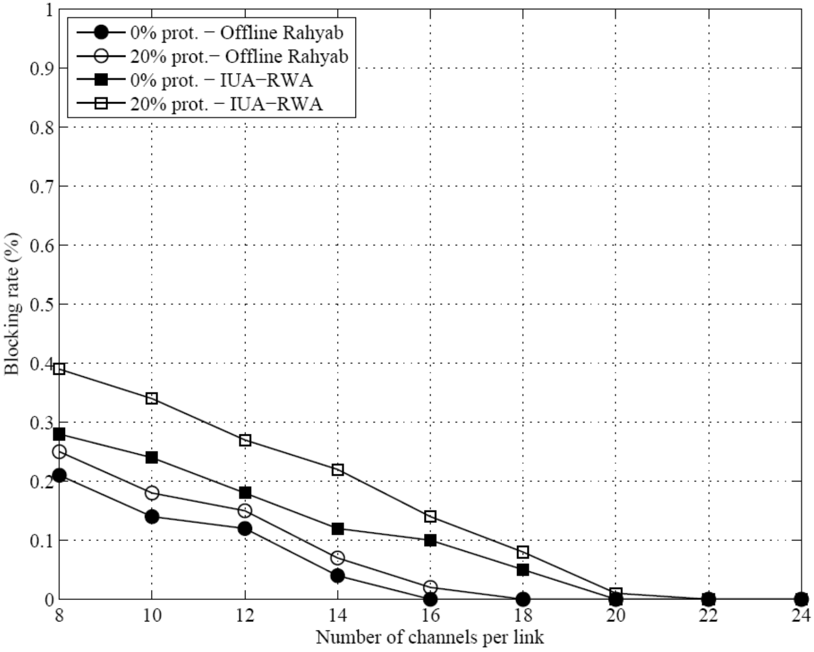


Figure 4-9: Blocking rate vs. number of channels per link (Internet-2).

4.4 Comparative Study

Most of the algorithms proposed in the literature consider the online (dynamic) version of the IA-RWA problem. In contrary, there are few works in the literature regarding the offline IA-RWA problem, as presented in Chapter 2. In general the algorithmic approach for the physical layer IA-RWA problem can be categorized either as sequential approach based on some heuristic or global optimization, which searches for an optimal solution [MCK+09]. The pros and cons of each approach are discussed in [S08].

Random Search RWA (RS-RWA) is a heuristic algorithm that was proposed in [EZK+06]. The main idea in [EZK+06] is to perform a sequential search to compute lightpaths for a given random order of connection requests (permutation) in the demand set. The set of available paths is an arbitrary set of k alternate shortest paths which are given for each pair of source destination nodes. The wavelengths are assigned according to the first-fit policy. Among a number of random order of connection requests the one that achieves the lowest lightpath blocking, is selected. Once a set of accepted lightpaths is found, the physical signal quality is verified.

ILP-RWA is an optimization-based algorithm that was studied in [KTM+05], [TVM+04]. The RWA problem is formulated as an ILP problem. It is a global optimization algorithm, which for a given set of lightpath requests finds an optimal RWA over available paths and wavelengths. The set of candidate paths consists of k-shortest paths (between each pair of nodes), which are calculated based on some impairments-aware link cost metric. The link costs correspond either to the individual impairments [KTM+05], or are calculated as a link Q-factor [TVM+04]. The optimization criterion is the minimization of link usage subject to the network layer constraints.

An impairments-aware offline RWA algorithm that assigns Q-factor costs to links before solving the problem is proposed in [MST+07]. In that work, which is based on [KTM+05], k-shortest routes are computed considering a Q-penalty value as the link costs. Then, the wavelength that maximizes the Q value is selected to serve each connection request. Since the wavelength assignment is not performed jointly for all connections, a worst case assumption for the interference among lightpaths is used. Therefore, the proposed algorithm does not take into account the actual interference among lightpaths and does not truly optimize the performance, since it assumes worst case interference.

In this section the RS-RWA algorithm [EZK+06] and an ILP-based RWA (ILP-RWA) algorithm [KTM+05] are considered as two offline IA-RWA algorithms from literature (both extended with path protection capability) because they use different approach to address the IA-RWA problem. Then their performance are compared with that of the offline Rahyab IA-RWA algorithm under the same traffic, network and physical layer conditions.

4.4.1 Enhancement of Selected Algorithms

RS-RWA [EZK+06] is a heuristic IA-RWA algorithm, in which for a number of different random ordering of the connection requests (traffic demand set), the algorithm performs sequential processing of connection requests with the goal to find the lightpath assignment that achieves the lowest blocking rate.

Each of these random ordering of the connection requests is considered as a permutation of the demand set. Once a set of such lightpaths is found, the physical signal quality is verified and the lightpaths that do not comply with the QoT requirements are rejected. Here two enhancements to improve the performance (in terms of blocking rate) of this algorithm (RS-RWA-Q) is presented and support for dedicated path protection (RS-RWA-QP) consideration is added. The processing steps of RS-RWA are as follows:

1. Initialization: for each pair of source-destination nodes calculate *k* alternate shortest paths.
2. Generate a permutation vector and arrange connection requests in a random order defined by the permutation vector.
3. For given permutation vector, find RWA according to the following subroutine:
    a. Take first request from the permuted set of requests.
    b. Select the next computed path from the set of paths.
    c. Select first available wavelength on a given path according to the First-Fit policy.
    d. If no wavelength is available, select next path and repeat step c); if the request is not supported by any path and wavelength, reject it.
    e. Repeat steps b) to d) for all lightpath requests.
4. Repeat steps 2)-3) *MaxTries* times (e.g., 100) for different permutation vectors.
5. Select the RWA solution that achieves the lowest connection blocking.
6. Verify the QoT of the accepted lightpaths using a physical layer performance evaluator (Q-Tool). All lightpaths with a QoT value below a certain threshold are blocked.

Here the RWA subroutine of RS-RWA (step 3) only considers the network-layer constraints, (i.e., the availability of wavelengths on candidate paths). Moreover, the best RWA is found based on the blocking performance only at the network layer. Therefore the performance of the physical layer is not incorporated in the RWA process and the QoT verification is performed just as a last verification step on the final RWA solution.

In order to consider the impact of physical layer impairments in this algorithm, the RS-RWA is enhanced to RS-RWA-Q by performing QoT verification for each permutation of demand set (i.e., after step 3 above). This modification enables us to search at step 5 for the RWA solution that achieves lowest blocking rate, among all the permutations, considering both the network layer (i.e., resource availability) and physical layer constraints. In turn, to serve demands with dedicated path protection, the RS-RWA-Q is further enhanced to obtain the RS-RWAQP algorithm as follows. In the first step of this enhancement, in addition to the set of primary paths, a set of backup diverse paths is also computed (step 1). Protected demands are processed before unprotected demands. For each protected connection request, both primary lightpath and backup lightpath are searched similarly as in the RWA subroutine of RS-RWA. The search is performed until a pair of lightpaths is found such that one lightpath is on a primary path and the other lightpath is on the corresponding backup path. If such a pair of lightpaths cannot be established at the same time, the request is blocked. Finally, during the QoT verification phase, which is performed for each permutation, both primary and backup lightpaths are checked; if any of the two does not comply with the QoT requirements, the request is rejected. Unprotected demands are processed according to the RS-RWA-Q algorithm. The original RS-RWA and proposed enhancements (i.e., RS-RWA-Q and RS-RWA-QP) are indicated in the flow diagram (Figure 4-10) of RS-RWA algorithm.

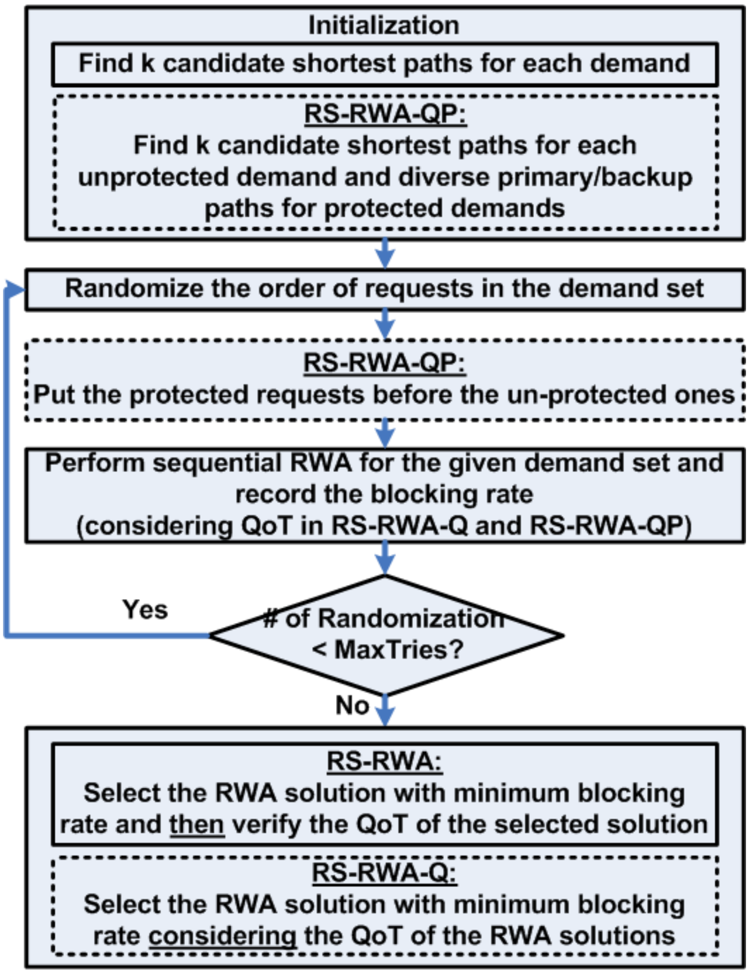


Figure 4-10: Flow chart of RS-RWA algorithm and proposed enhancements.

The main idea behind the ILP-RWA algorithm is to find an optimal RWA solution over a set of pre-computed paths and then perform QoT verification of candidate lightpaths using the physical layer performance evaluator (Q-Tool version 2.21, presented in Chapter 2). The RWA problem is formulated as a common ILP problem, i.e., subject to the network layer constraints, and physical layer constraints are not included directly into the set of constraints. Still the impairment-awareness property of the algorithm is in place with two considerations. First, the set of candidate paths is calculated based on some impairment-aware link cost metric and by means of a shortest path algorithm (e.g., the Dijkstra algorithm). The idea is to explore the paths which are less likely to experience signal distortions.

Secondly, the set of lightpaths obtained after the solution of the ILP procedure is checked with respect to the optical signal quality; and if a given lightpath does not comply with the QoT requirements, it is blocked.

Here extensions are proposed that decrease the blocking rate due to both the wavelength continuity and the physical layer performance constraints and also enable it to handle protected demand sets (i.e., lightpath requests with dedicated path protection). The relevant notation are introduced as follows:

Notations:

E	The set of edges (directed network links).
W	The set of wavelengths.
D	The set of demands; each demand corresponds to a pair of source-destination nodes.
P_d	The set of (primary) paths supporting demand *d*.
$P_d^{'}$	The set of backup paths supporting demand *d*.
P	The set of all paths; $P = \bigcup_{d \in D} (P_d \cup P_d^{'})$.

We assume $|P_d| = |P_d^{'}|, \forall d \in D$, and for each primary path $p \in P_d$ there is a unique backup path $p^{'} \in P^{'}{}_d$ defined according to the one-to-one mapping $\gamma(p) = p^{'}$ such that $\gamma(q) \neq p^{'}, \forall q \in P_d \setminus \{p\}$. Such a mapping allows us to represent pairs of disjoint primary and backup paths.

Variables:

$x_{pw} \in \{0,1\}$	A decision variable, equal to 1 if wavelength *w* on (primary) path *p* is assigned to an (unprotected) lightpath, and equal to 0 otherwise.
$y_{pw} \in \{0,1\}$	A decision variable, equal to 1 if wavelength *w* on primary path *p* is assigned to a protected lightpath, and equal to 0 otherwise.
$y^{'}_{pw} \in \{0,1\}$	A decision variable, equal to 1 if wavelength w on backup path *p* is assigned to a protected lightpath, and equal to 0 otherwise.
$x_{ew} \in \{0,1\}$	An auxiliary variable, equal to 1 if wavelength *w* on link *e* is used, and equal to 0 otherwise.
$x_d \in Z^+$	A slack variable which represents the number of not-accepted unprotected lightpath requests of demand *d*.
$y_d \in Z^+$	A slack variable which represents the number of not-accepted (i.e., blocked) protected lightpath requests of demand *d*.
$u \in Z^+$	A variable counting the number of links in which the most occupied wavelength (in the entire network) is used.

Coefficients and constants:

δ_{ep}	A coefficient which is equal to 1 if link *e* belongs to (primary) path *p*, and equal to 0 otherwise.
$\delta^{'}_{ep}$	A coefficient which is equal to 1 if link *e* belongs to backup path *p*, and equal to 0 otherwise.
h_d	The volume of (unprotected) demand d (i.e., the number of lightpath requests for a given pair of nodes).
h_d^P	The volume of protected demand d.
α	A big constant number used as a weighting coefficient in the multi-objective function to give a priority to the blocking objective of unprotected connection requests.
β	A big constant number used as a weighting coefficient in the multi-

objective function to give a priority to the blocking objective of protected connection requests.

1) ***Basic problem formulation***: In the beginning, a basic ILP formulation of the RWA problem (ILP-RWA) without protected demands is presented. The formulation has been slightly modified with respect to the one presented in [KTM$^+$05]. The reason is that in [KTM$^+$05] there is no link capacity constraint imposed and, as a consequence, all the requests are assumed to be served by the network. Moreover the optimization criterion is the minimization of overall link usage. Since the main focus is on the blocking rate performance metric, additional link capacity constraints is imposed and the problem objective is modified.

The ILP-RWA problem objective is to minimize the number of lightpath requests blocked due to inability to find a free wavelength:

$$\text{minimize} \sum_{d \in D} x_d , \tag{4-1}$$

subject to the following constraints:

- Input traffic constraints:

$$\sum_{p \in P_d} \sum_{w \in W} x_{pw} + x_d = h_d , \forall d \in D \tag{4-2}$$

For each demand d, available wavelengths on paths from set P_d are assigned to lightpath requests h_d. Note that since x_{pw} is a binary variable, each path-wavelength pair can support only one lightpath. Also the wavelength continuity constraint is imposed implicitly since decision variable x_{pw} defines the entire lightpath (i.e., the assignment of wavelength w on path p). Slack variable x_d is introduced to count the number of lightpath requests that cannot be supported (i.e., blocked).

- Wavelength assignment constraints:

$$\sum_{p \in P} \delta_{ep} x_{pw} = x_{ew} , \forall e \in E, \forall w \in W \tag{4-3}$$

Only one lightpath may use wavelength w on link e at the same time; note that since variable x_{ew} is binary this bound is (implicitly) imposed. Range constraints:

$$x_{pw} \in B^{|P| \times |W|}, x_{ew} \in B^{|E| \times |W|}, x_d \in Z_+^{|D|}, \tag{4-4}$$

where B denotes the binary set (B = 0,1).

2) ***Formulation enhancements***: The main drawback of ILP-RWA is the lack of any (explicit or implicit) impairment aware information involved into the optimization process. In particular any feasible RWA solution that satisfies the minimum blocking performance objective of ILP-RWA is equally good. In fact, in the presence of physical layer impairments some solutions (e.g., those that make use of a small subset

of available wavelengths which, in addition, are neighbour wavelengths) may be more susceptible to crosstalk effects than the solutions that try to make use of the entire pool of wavelengths and explore wavelengths evenly. Intuitively, when the assignment of wavelengths is diversified over the network, it gives more chances for a disperse wavelength occupation in network links than, for instance, in case of first-fit assignments [HBP+07].

In order to induce the ILP algorithm to look for such solutions the problem is reformulated by introducing additional constraints on the maximal usage of a wavelength in the network and by representing the objective as a multi-objective function. This new formulation, denoted as ILP-RWA-LU, is defined as follows:

$$\text{minimize } \alpha \sum_{d \in D} x_d + u, \tag{4-5}$$

subject to (4-2)-(4-4), and additional maximal wavelength usage constraints:

$$\sum_{e \in E} x_{ew} \leq u, \forall w \in W, \tag{4-6}$$

$$u \in Z^+. \tag{4-7}$$

In this minimization problem priority is given to the blocking objective (it is assumed that $\alpha >> 1$) and, in the second place, the focus will be on the usage of the most occupied wavelength in the network, which is represented by variable u in the objective function. Constraint (4-6) allows finding such maximal usage, since the inequality (4-6) has to be satisfied for all wavelengths, and constraint (4-7) is integrality constraint. Note that by minimizing the maximal wavelength usage we implicitly induce the ILP solver to look for the solutions that try to balance the overall wavelength usage and, as a consequence, diversify the assignment of wavelengths in network links.

3) ***Protection extensions***: The ILP formulation in [KTM+05] does not take into account the existence of protected demands. Here an extended formulation (ILP-RWA-LUP) is presented to handle such demands with dedicated path protection. In particular a protected connection request requires the assignment of both a primary and a backup lightpath; in case that no such simultaneous assignment is feasible, the request is blocked. The optimization objective is formulated as:

$$\text{minimize } \alpha \sum_{d \in D} x_d + \beta \sum_{d \in D} y_d + u. \tag{4-8}$$

The multi-objective function of (4-8), which is similar the one in ILP-RWA-LU, incorporates the sum of unaccepted protected demands apart from counting the sum of unaccepted non-protected demands and the maximal wavelength usage. It is considered that $\beta >> \alpha$ and $\alpha >> 1$, so that the acceptance priority is given first to protected and then to unprotected demands. Accordingly, constraints (4-2)-(4-4) and (4-6) are reformulated:

- Unprotected and protected input traffic constraints:

$$\sum_{p\in P_d}\sum_{w\in W} x_{pw} + x_d = h_d, \forall d \in D \tag{4-9}$$

$$\sum_{p\in P_d}\sum_{w\in W} y_{pw} + y_d = h_d^P, \forall d \in D \tag{4-10}$$

Primary lightpaths are assigned to both unprotected and protected demands.

- Wavelength assignment constraints:

$$\sum_{p\in P} \delta_{ep}\left(x_{pw} + y_{pw}\right) + \sum_{p\in P_d^{'}} \delta_{ep}^{'} y_{pw}^{'} = x_{ew}, \forall e \in E, \forall w \in W. \tag{4-11}$$

Again, only one lightpath, either primary or backup, may use wavelength *w* on link *e* at the same time.

- Wavelength usage constraints, which have the same application as (4-6) and (4-7) in ILP-RWA-LU formulation:

$$\sum_{e\in E} x_{ew} \le u, \forall w \in W, \tag{4-12}$$

$$u \in Z^+. \tag{4-13}$$

- Backup lightpath selection constraints:

$$\sum_{w\in W} y_{pw} - \sum y_{p^{'}w}^{'} = 0, \forall d \in D, \forall p \in P_d, p^{'} = \gamma(p). \tag{4-14}$$

Constraint (4-14) states that for each protected connection, a primary lightpath is assigned if and only if a backup lightpath is assigned. The selection of primary path p induces the selection of backup path p0 according to the mapping $\gamma(.)$.
Finally:

$$x_{pw} \in B^{|P|\times|W|}, y_{pw} \in B^{|P|\times|W|}, y_{pw}^{'} \in B^{|P|\times|W|}, x_{ew} \in B^{|E|\times|W|}, x_d \in Z_+^{|D|}, u \in Z^+, \tag{4-15}$$

which are range constraints imposed on problem variables.

4.4.2 Assumptions and Simulation Parameters

The network topology in the simulation studies is DTNet (See Appendix A). This network has 14 nodes and 23 bidirectional links, with an average node degree of 3.29. The line rate in this network is assumed to be 10 Gbps. A heterogeneous network topology is assumed in which the node and link architectures have different impact and contributions on physical layer impairments. The offered load in the network is defined as the ratio between the number of lightpath demands divided by the number of pairs of nodes in the network. The unit traffic load corresponds to the demand set where there is a lightpath request between each pair of (distinct) source destination nodes. However, it is possible to have more than one lightpath request between a given source-destination pair.

The evaluation is performed for the values of traffic load between 0.5 and 1.0 with a step of 0.1, corresponding here to the establishment of 91 to 182 lightpaths. For each load value 50 different demand sets of random (static) lightpath requests is considered. In case of protected demand sets, 20% of the demands were requesting a dedicated protection lightpath between source and destination.

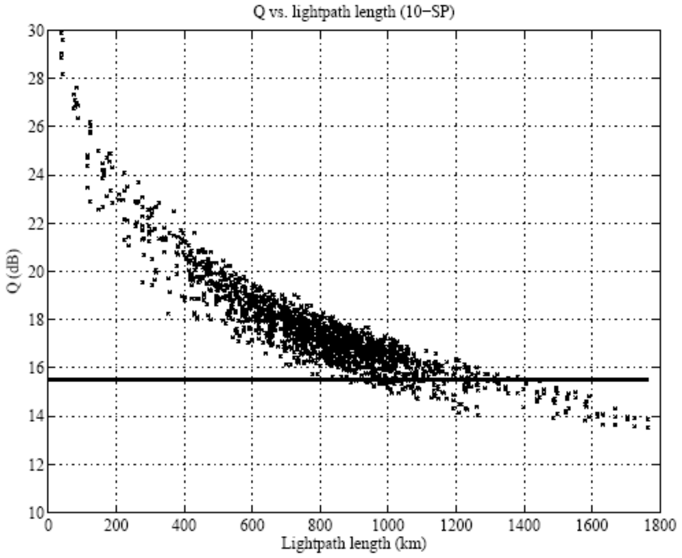


Figure 4-11: Q-factor value vs. lightpath length ($Q_{Threshold}$=15.5 dB).

The input power to the links is -4 dBm and 3 dBm per channel for Dispersion Compensation Fibre (DCF) and Standard Single Mode Fibre (SSMF) fibres respectively. It is also assumed that pre-dispersion compensation of -400 ps/nm is considered in the links. The SSMF amplifier span length in each link was set at 100 km, followed by a DCF segment that under-compensates the dispersion of the preceding SSMF of a value of 30 ps/nm/km. At the end of each link the accumulated dispersion is fully compensated. It was assumed that the SSMF fibres have a dispersion parameter of 17 ps/nm/km and attenuation of 0.25 dB/km. The DCF segments have a dispersion parameter of D = 80 ps/nm/km and an attenuation of 0.5 dB/km. The PMD coefficient for all fibre segments is set to 0.1 $ps/\sqrt{km}$ .The channel spacing was set to 50 GHz. The noise figures that were utilized in simulation studies had a mean value of 6 dB with a variation of 1 dB. In a similar manner the signal-to-crosstalk ratio had a mean value of -32 dB with a deviation of 2 dB around this mean value in each node. The threshold value for computing the impact on Q-factor (i.e., Qthreshold) is 15.5 dB (corresponding to BER=10^{9} without FEC). In Figure 4-11 the Q-factor value of 10 shortest paths between all possible pairs of the nodes in the network is depicted. Without considering the impact of other established lightpaths, the maximum optical reach is about 1500 km in this network.

Two versions of the RS-RWA algorithm and the enhanced versions are implemented. In both cases *MaxTries*(=100) permutations of each demand set are examined. The candidate shortest paths (SP) are calculated considering the link length as the link cost metric. The number of paths that are considered between each pair of source destination nodes is k = {2, 10} for RS-RWA, k = 10 for RS-RWA-Q, and k = {1,2} for ILP-RWA and k = {1, 2, 3} in ILP-RWA-LU. Note that for k = 1 the routing sub-problem of ILP-RWA is relaxed and the algorithm performs as a wavelength assignment algorithm. It is assumed that $\alpha = |E| + 1$ and $\beta = \alpha\left(\sum_{d \in D} h_d + 1\right) + 1$. The offline Rahyab algorithm considers k = 10 shortest path between each source-destination pair in its candidate set and if the demand is protected, k = 2 diverse routes between each pair are computed.

4.4.3 Results

In order to compare the performance of the selected algorithms the blocking rate of demand sets is considered as the key performance metric. Blocking rate is the ratio of number of blocked demands to the total number of demands in a given demand set. More specifically, metrics that characterize the quality of the solutions obtained by the IA-RWA algorithms are: a) Blocking rate for a given number of wavelengths as a function of the traffic load and b) Blocking rate for a given load as a function of the number of channels per link.

The blocking rates of three variations of RS-RWA algorithm are shown in Figure 4-12. The performance of the enhanced RS-RWA is clearly better than the original RS-RWA algorithm (with k=2 and k=10 shortest path computation). For instance at Load=0.7 the performance of RS-RWA-Q algorithm is 44% better than RS-RWA (10 SP). The main reason for this improvement is the consideration of physical layer impairments for each permutation of the demand set. Therefore the RSRWA-Q selects the RWA solution that achieves the lowest blocking rate among the other candidate permutations, while in RS-RWA algorithm, the RWA decisions are made without consideration for the performance of the physical layer.

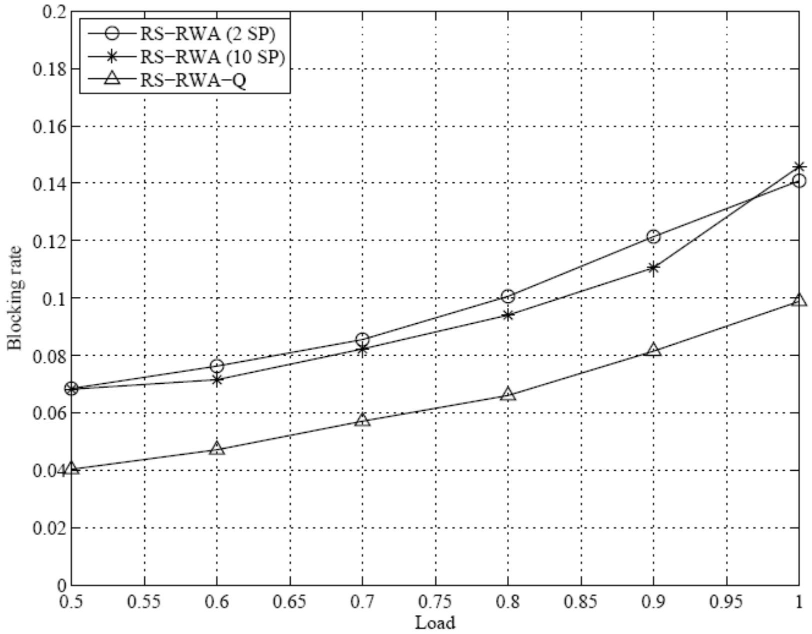


Figure 4-12: Blocking rate vs. various load value for three variations of RS-RWA.

This improvement is also observed when the blocking rate of RS-RWA algorithms is considered as a function of available channels per fibre link for a specific load value in the network. The result of this experiment is depicted in Figure 4-12. Even with more channels per link, the blocking rates of the RS-RWA-Q algorithms do not decrease. The small fluctuation in blocking rate is due to the slightly different contribution of crosstalk that could occur for each scenario of available channels per fibre. This behaviour is mainly caused by the first-fit wavelength assignment policy in RS-RWA-Q, which always allocates successive (neighbour) wavelengths, no matter how many wavelengths are available in the link, thus results in the crosstalk effect and eventually same level of blocking rate.

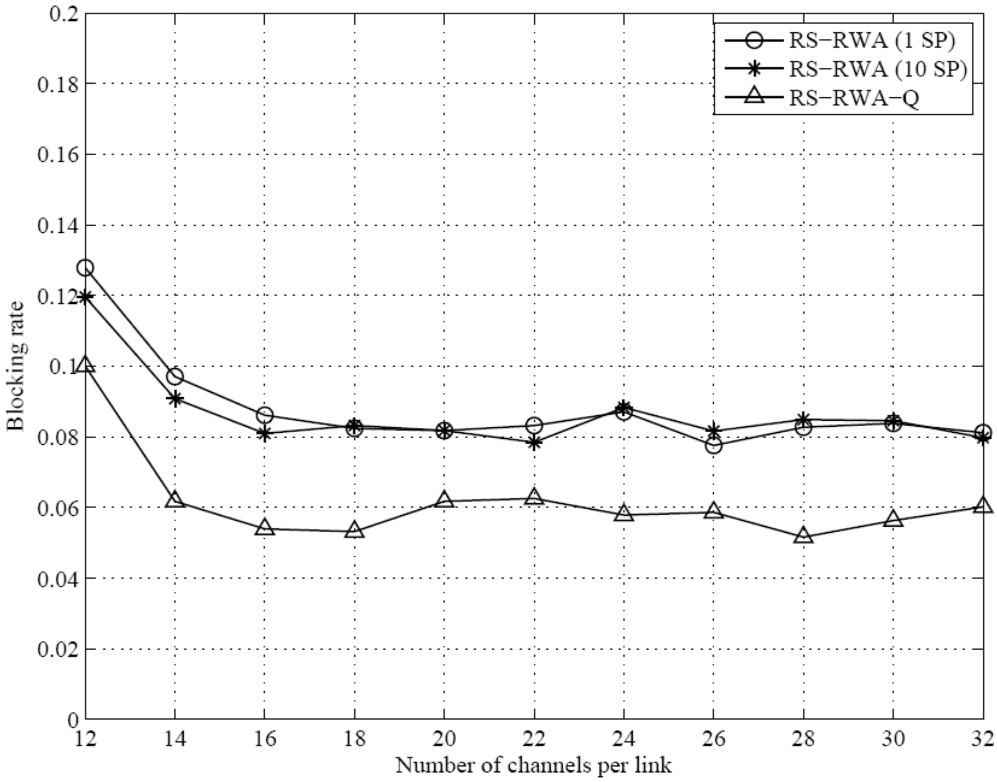


Figure 4-13: Blocking rate vs. number of channels per fibre link (Load =70%).

The same study was performed among the various ILP-RWA algorithms. Figure 4-15 depicts the blocking rate of different variations of ILP-RWA and ILP-RWA-LU algorithms. It can be observed that the performance of the ILP-RWA-LU (1 SP) is better than the original ILP-RWA algorithms (both 1 SP and 2 SP).

Another important observation in this result indicates that increasing the number of candidate shortest paths also increases the blocking rate of ILP-RWA and ILP-RWA-LU algorithms. Increasing the size of the candidate paths helps the ILP-RWA algorithm to easier find a globally optimized RWA solution, for which the satisfaction of the QoT requirement is not guaranteed. Larger pool of candidate paths, coupled with lack of QoT verification paves the way for higher probability of picking a candidate path that will not satisfy the QoT requirement. Better performance can be observed for the ILPRWA- LU algorithm, in which an additional objective (the usage of the same wavelength in the network), is introduced. This objective makes the algorithm diversify the assignment of wavelengths and therefore decrease the impact of physical impairments that are caused due to the lightpaths crosstalk.

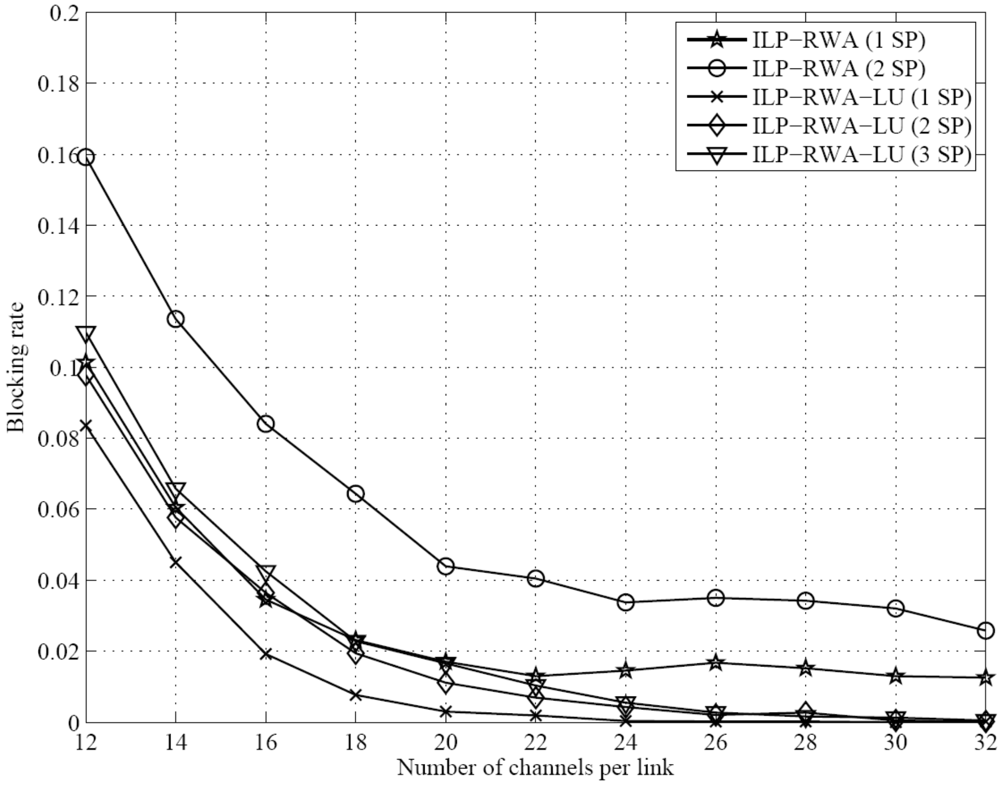


Figure 4-14: Blocking rate vs. number of channels per link for five variations of ILP-RWA algorithms (Load=70%).

In Figure 4-14 the blocking rate performance of various ILP-RWA algorithms for a given amount of load in the network is better than the original ILP-RWA algorithms (both 1 SP and 2 SP). Another important observation in this result indicates that increasing the number of candidate shortest paths also increases the blocking rate of ILP-RWA and ILP-RWA-LU algorithms. Increasing the size of the candidate paths helps the ILP-RWA algorithm to easier find a globally optimized RWA solution, for which the satisfaction of the QoT requirement is not guaranteed. Larger pool of candidate paths, coupled with lack of QoT verification paves the way for higher probability of picking a candidate path that will not satisfy the QoT requirement. Better performance can be observed for the ILP-RWA-LU algorithm, in which an additional objective (the usage of the same wavelength in the network), is introduced. This objective makes the algorithm diversify the assignment of wavelengths and therefore decrease the impact of physical impairments that are caused due to the lightpaths crosstalk.

In Figure 4-15 the blocking rate performance of various ILP-RWA algorithms for a given amount of load in the network is depicted as a function of the available channels per fibre link.

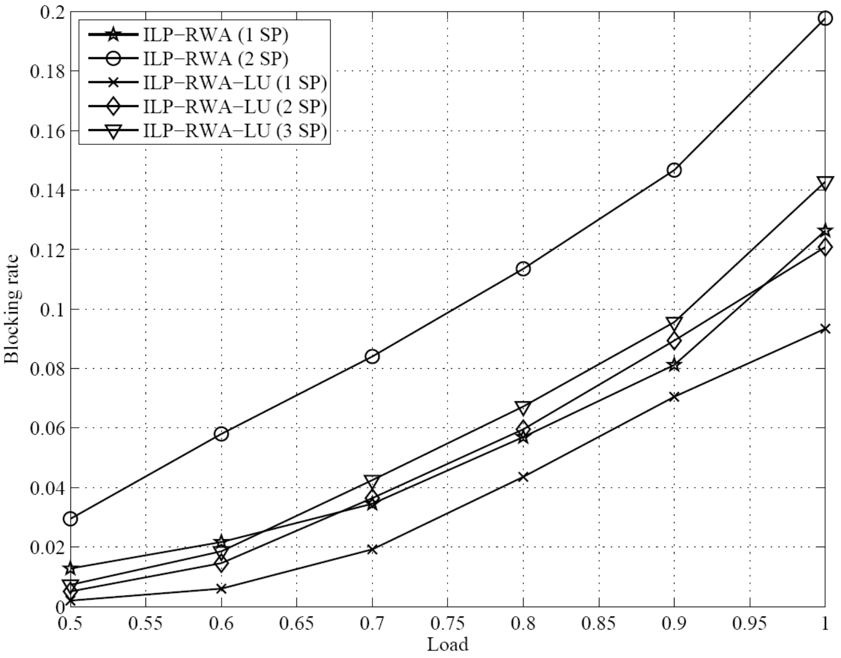


Figure 4-15: Blocking rate vs. Load for five variations of ILP-RWA algorithms (W=16).

In general by increasing the number of available resources per each fibre link the chance of accommodating the given load in the network is increased, this can be therefore translated to lower blocking rate. The ILP-RWA-LU assigns wavelengths more diversely that causes lower interaction between neighbouring lightpaths and thus lower blocking rate. Again note that increasing the number of candidate paths does not improve the performance of different variations of the ILP-RWA-LU algorithms. As mentioned before, increasing the number of candidate paths simply helps the ILP formulation to find an RWA solution, which does not necessarily satisfy the QoT requirement.

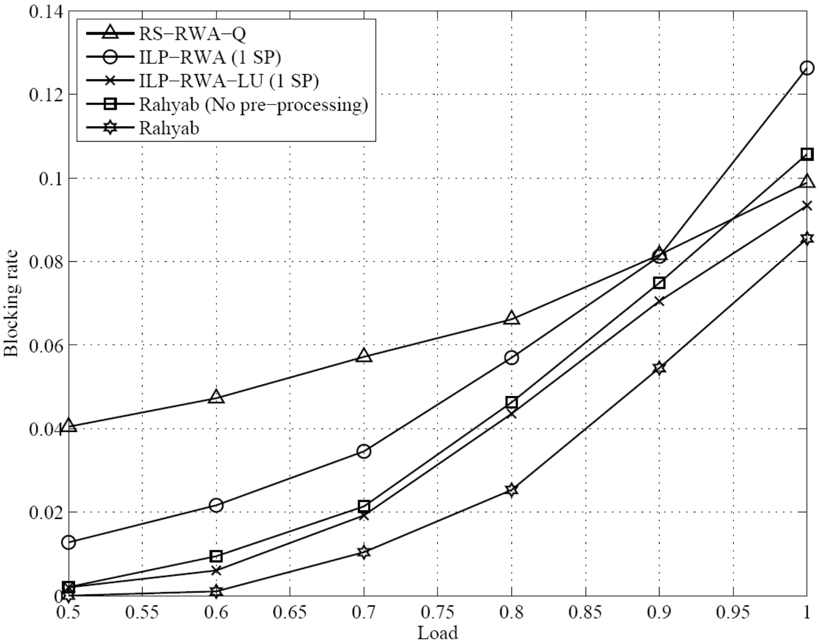


Figure 4-16: Blocking rate vs. load for selected IA-RWA algorithms (W =16).

After identifying the impact of proposed enhancements in RS-RWA and ILP-RWA algorithms, the performance evaluation study were repeated considering the Rahyab algorithm. In Figure 4-16 and Figure 4-17 the blocking rate of selected IA-RWA algorithms is presented. In spite of these enhancements, the RS-RWA-Q algorithm has the worst performance compared with other algorithms. The main reasons for this low performance reside in the random selection of the demand set, without considering a particular order for demand processing and also the first-fit wavelength assignment policy utilized in this algorithm. The first-fit policy simply ignores the negative impact of assigning neighbouring channels on lightpath (with potentially many common links). The ILP-RWA algorithm finds a globally optimized RWA solution. This global optimization policy performs well for low load value, however by increasing the load, the probability of finding a globally optimized solution that does not satisfy the QoT requirement increases too. This is observed for the loads 0.9 and 1.0, in which the performance of the ILP-RWA is comparable or even worse than the RSRWA algorithm. The ILP-RWA-LU enhancement introduces an additional objective (the maximal usage of a wavelength), which makes the algorithm diversify the assignment of wavelengths and leads to lower blocking rate.

In case of unprotected demands only, obtained results show that the blocking after the ILP procedure is lower if more SPs are available (e.g., 0% blocking with 3 SPs vs. 5% blocking with 1 SP, under 100% load). On the other hand, quality blocking is much higher for scenarios with more SPs given (adequately, 14% for 3 SP vs. 4% for 1 SP). Then, the overall blocking, which is the sum of both blocking components, leads to the presented results. Finally the Rahyab algorithm performs better than selected algorithms due to several reasons. The demand pre-processing part of Rahyab rearranges the order of the demands in the demand set in a way that demands that require more resources (i.e., longest shortest path first) are processed first. The impact of the demand pre-processing can be observed in these figures for two cases of Rahyab algorithm (with and without demand pre-processing). The wavelength assignment policy in Rahyab considers the impact of establishing the new lightpath on all the already established lightpaths. This adaptive wavelength assignment, with the goal of establishing a lightpath with minimum impact on other established lightpaths gives more room to accommodate lightpaths in the network, and leads to lower blocking rate. The k-shortest path engine enables Rahyab to find a rich set of candidate lightpaths between source and destination. The downside of Rahyab is the extensive utilization of the Q-Tool, which itself is very computationally intensive; however, since the working setup is for offline network dimensioning, computation time is of secondary importance and Rahyab is adapted to offline network design.

The next set of results summarizes the blocking rate performance of selected algorithms with consideration of protected demands. In Figure 4-18 and Figure 4-19 the blocking rate of the selected algorithms vs. load and also vs. number of channels per fibre link is depicted. In order to reveal the impact of pre-processing phase of Rahyab algorithm, the results of Rahyab algorithm, without demand pre-processing step have been also included.

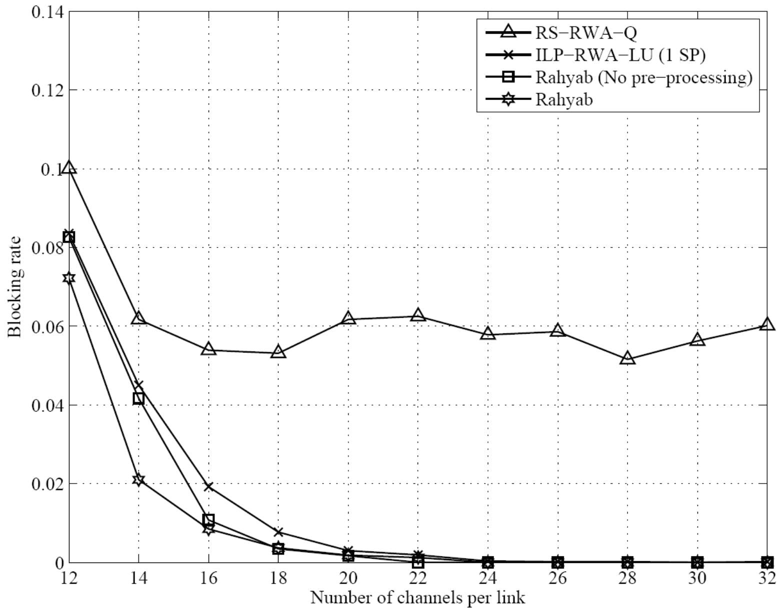


Figure 4-17: Blocking rate vs. number of channels per link for selected IA-RWA.

For small to medium amount of load, the diverse routing engine and adaptive wavelength assignment module compensate for the lack of pre-processing block. However by increasing the load, the mentioned components of the Rahyab algorithm are not able anymore to avoid higher blocking rate. The impact of Rahyab pre-processing module can be observed in Figure 4-18 when in particular there are low numbers of channels per fibre. However by increasing the number of channels per fibre, the diverse routing engine and adaptive wavelength assignment compensate for the lack of pre-processing module. The same impact was observed in other comparisons but it is only reported in these two figures to maintain the completeness of results and clarity.

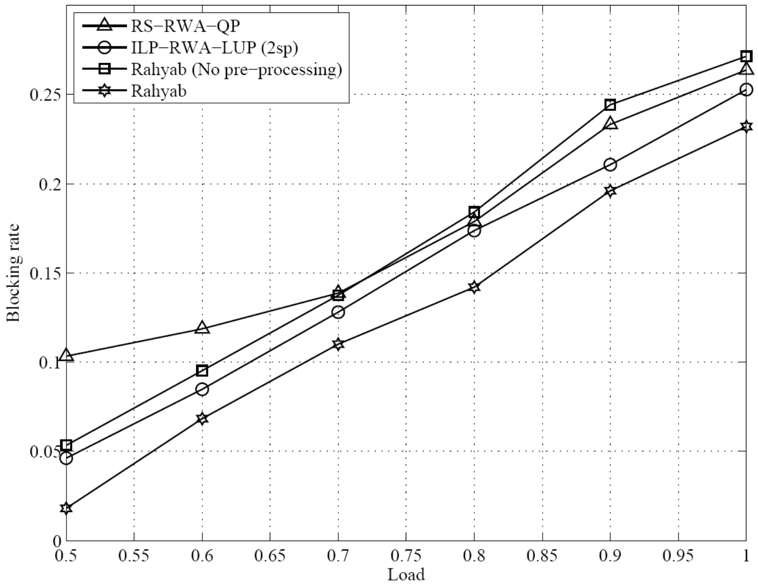


Figure 4-18: Blocking rate vs. load for selected IA-RWA algorithms (W =16) and 20% protected demands.

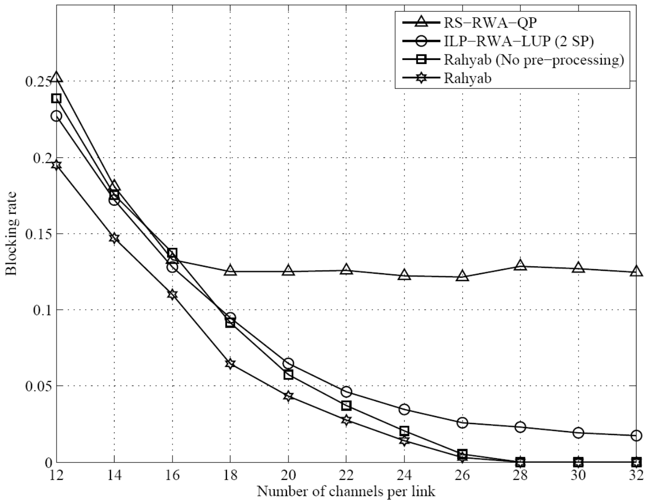


Figure 4-19: Blocking rate vs. number of channels per link for selected IA-RWA algorithms (Load=70%) and 20% protected demands.

The blocking rate of ILP-RWA-LUP (2 SP) is higher than Rahyab algorithm but lower than RS-RWA-QP. ILP-RWA-LUP (2 SP) performs better than ILP-RWA-LUP (1 SP) (not reported here). The dedicated path protection requires two paths for each demand and therefore ILP-RWA-LUP (2 SP) has a better chance to find the primary and backup path when performing the ILP procedure. The results for ILP-RWA-LUP (2 SP) and ILP-RWA-LUP (3 SP) (also not reported here) are very similar and vary only slightly for different loads. Figure 4-19 shows that the Rahyab algorithm is able to serve all demands when the number of channels per link is *w* =28. RS-RWA-QP algorithm utilizes a first-fit wavelength assignment policy, which tries to allocate wavelengths with a predefined order. This increases the impact of crosstalk related impairments and therefore the blocking rate does not reach the non-blocking (0%) level.

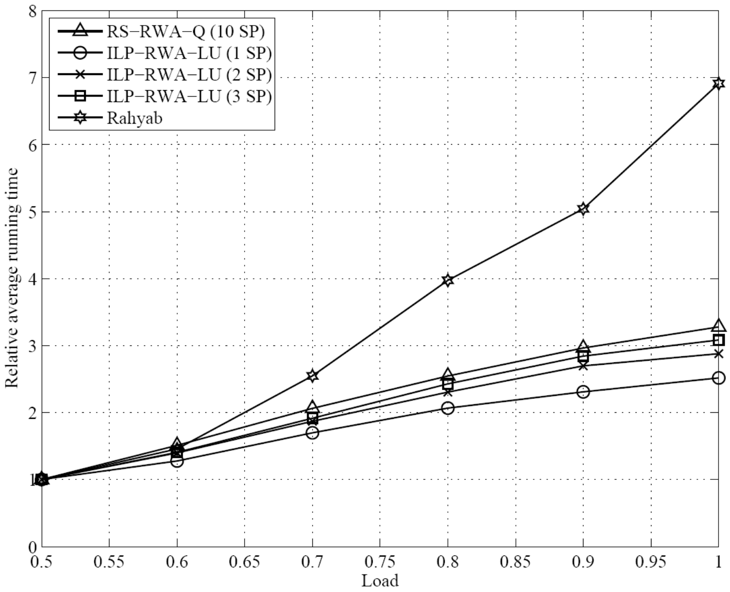


Figure 4-20: Relative average running time vs. load (w=16).

In order to evaluate the time complexity and scalability of the algorithms the relative average running time performance metric is defined. This metric is the ratio of the average running time of a given algorithm for a certain load ρ over the average running time of the same algorithm for the reference load (i.e., ρ=0.5). This relative metric removes the dependency of the running time of an algorithm to the performance of a particular hardware platform. The relative average running time of ILP-RWA-LU, RS-RWAQ, and Rahyab are depicted in Figure 4-20. The ILP-RWA-LU has the best relative running time compared to RS-RWA-Q and Rahyab algorithms. The ILP-RWA-LU belongs to the global optimization techniques, in which the impact of the physical layer impairments is indirectly considered in the ILP formulation. Its relative running time depends on the performance of the utilized ILP solver and the performance of the Q-Tool for verification step. The complexity of the RS-RWA-Q algorithm is dominated by the required time for verification of QoT of the candidates. However as the load increases the size of the demand set is increased and the final QoT evaluation is more time consuming. Rahyab algorithm intensively utilizes the Q-Tool and given the complexity of the analytical models inside the Q-Tool the running time of Rahyab is much higher than other selected algorithms. For a single unprotected demand, the maximum number of Q-Tool invocation is equal to the number of candidate paths in each LNG (i.e., $k \times W$ in which k is the number of candidate paths and W is the number of wavelengths per link). However the running time of Q-Tool increases exponentially by the increase of number of established lightpaths that should be fed to the Q-Tool for QoT evaluation. The running time of Rahyab can be dramatically decreased by utilizing high-performance (e.g., FPGA accelerated) QoT estimators.

4.4.4 Discussions

The offline IA-RWA algorithms play an important role in serving the demands with possibly minimum amount of blocking. In this section the RS-RWA heuristic and proposed enhancements (RS-RWA-Q, RS-RWA-QP), the ILP-RWA and proposed enhancements (ILP-RWA-LU, ILP-RWA-LUP), along with a novel algorithm (called Rahyab) were evaluated. The enhancement to the RS-RWA heuristic (i.e., RS-RWA-Q) reduced the blocking rate of demands by an average of 35% for different loads compared to the original scheme (i.e., RS-RWA). The performance of ILP-RWA-LU (1 sp) formulation (i.e., enhanced ILP-RWA) is also improved by 71%. The Rahyab algorithm performs better than the other two algorithms with respect to the blocking rate performance metric. For instance when the offered load to the network is 80%, the blocking rate of Rahyab algorithm is decreased by 61% and 42% compared to RS-RWA-Q and ILP-RWA-LU algorithms respectively. When the number of channels were limited only to 14 channels per link (i.e., w =14) and the demand set included both the protected and un-protected demands, the performance of Rahyab algorithm was better than RS-RWA-QP and ILP-RWA-LUP by 22% and 15% respectively. RS-RWA-Q and RS-RWA-QP algorithms find an optimum permutation of demand set that leads to lower blocking rate, however proper ordering of demands are not considered in it. Furthermore the wavelength assignment policy in this algorithm is first fit, which increases the chance of unwanted crosstalk between neighbouring lightpaths. ILPRWA-LU performs better than RS-RWA-Q, mainly thanks to the diversification of wavelength assignments, however the adaptive wavelength assignment and proper ordering of the demand set in Rahyab helps it perform better compared to its ILP-based counterpart.

The demand pre-processing technique can be further enhanced with more sophisticated schemes. One possible approach could be the use of global optimization (e.g., liner programming) to find an optimum order for demands. Proper integration of IA-RWA algorithms with control plane and its impact on control plane operation are among the ongoing research activities.

4.5 Impairment-Aware Rerouting

In dedicated protection, spare resources are specifically allocated for a particular demand. If a demand is brought down by a failure, it is guaranteed that there will be available resources to recover from the failure, assuming that backup resources are available and have not failed too. Considering the protected and un-protected (restorable) demands in an optical network, in this section a re-routing strategy is presented, which maximizes the number of successful re-routed lightpaths that are affected by the failure in the network. The main assumption here is that the failure localization algorithm is able to identify and localize the failed link in the network. The localized failure may affect some of the currently established lightpaths. For example if the considered failure is due to a fibre cut, then all established lightpaths, which are traversing the failed link will be affected and should be re-routed.

However the critical issue in re-routing is the impact of re-routing these lightpaths (i.e., the affected ones) on the currently established lightpaths. If the re-routing strategy does not consider these impacts, then it is possible that re-routing strategy introduces a domino effect on the currently established lightpaths. In order to avoid this issue and properly address the rerouting, the following re-routing strategy as depicted in Figure 4-21 is proposed.

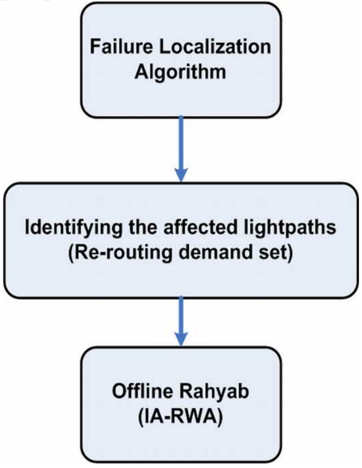


Figure 4-21: Impairment-aware re-routing strategy.

The proposed impairment aware re-routing strategy minimizes the impact of the rerouting of the affected lightpaths on the already established lightpaths (i.e., active lightpaths). The trigger point of this strategy is the outcome of the failure localization algorithm. Following the failure localization procedure, the affected lightpath(s) will be identified. Since the current state of the network is known, it is possible to identify the lightpaths which are affected by the detected failure. Since there are existing and active lightpaths in the network, the next step of the impairment aware re-routing strategy apply a specific pre-processing on the lightpath(s) that are affected by the failure. The rerouting demand set is fed to the offline Rahyab. This way, the rerouting problem is considered as an impairment aware planning problem with a limited size demand set of affected lightpaths.

In order to evaluate the performance of the proposed re-routing strategy, a simulation study is performed based on the DTNet topology (Defined in Appendix A). A heterogeneous network topology is assumed, in which the node and link architectures have different impact and contributions on the physical layer impairments. In order to evaluate the performance of the physical layer (i.e., QoT), Q-Tool (ver 3.33) is utilized. In addition to the impairment aware (IA) re-routing strategy, an impairment un-aware re-routing mechanism is considered for comparison purposes. The impairment unaware algorithm does not consider the pre-processing and also does not consider the impact of establishing the candidate lightpath on the currently established (i.e., active) lightpaths. It simply computes the shortest path that is also able to satisfy the wavelength continuity constraint. The wavelength assignment for the IUA-RWA re-routing scheme is first fit.

The performance metric that have been extracted from the simulation studies is the number of successful re-routing of demands over the total number of re-routing request. This metric is called as the successful re-routing rate. This metric was measured for various amount of the load in the DTNet. The load varies from 0.5 to 1.0 (with steps of 0.1) where the load value of 1.0 is defined as a demand set of 182 lightpaths. Considering the DT network with 14 nodes, the total number of lightpath between each possible pair of the nodes will be summed to 182 demands. Other load values are scaled accordingly. For each load value a random link failure was considered and based on the location of the link a different demand set (set of affected lightpaths that should be re-routed) was prepared for feeding to impairment aware rerouting engine. This experiment was repeated for 50 times for each load value and then the average successful re-routing rate for each load value was computed.

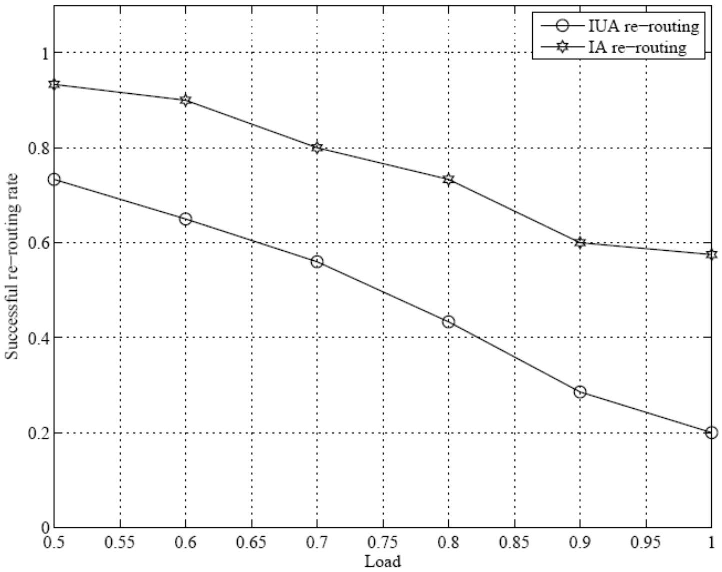


Figure 4-22: Successful re-routing rate vs. load.

The simulation results are depicted in Figure 4-22. It can be observed that when the pre-processing of the affected lightpaths and also the impairment aware re-routing strategy for various amount of load is considered, higher success rate for re-routing of demands can be achieved. Furthermore the IA re-routing strategy finds a candidate lightpath that introduces the minimum impact on the currently established lightpaths. When the load value in the network is low (i.e., 0.5~0.6) the success rate of the IA re-routing scheme is better by roughly 27%, while under high network load condition (i.e., 0.8) the gain of IA re-routing over the IUA rerouting is amounted to 70% improvement.

4.6 Chapter Summary

In this chapter the contributed novel algorithm for impairment aware network planning (Offline Rahyab) was presented along with its performance compared with impairment unaware and two impairment aware algorithms from literature. As mentioned in the introduction, the RWA problem is usually considered fewer than two alternative traffic models. When the set of connection requests is known in advance, the problem is referred to as network planning (or *offline* or *static* RWA), while when the connections arrive randomly and are served on a one-by-one basis the problem is referred to as network operation (*online* or *dynamic* RWA). The offline Rahyab algorithm solves the offline traffic problem in a sequential manner. Initially, it orders the connection requests according to some appropriate criterion and then serves the connections on a one-by-one basis. The demands are served in a way that the impact of establishing each demand (lightpath establishment) on the currently established lightpaths will be minimized.

Offline Rahyab demonstrated good wavelength utilization and blocking performance when the number of wavelengths is limited; however, as the traffic load increases its ability to find zero blocking solution is not that good, due to the fact that it does not optimize the lightpaths for all connections jointly, but on a one-by-one basis. An advantage of this heuristic is that it can provide different protection levels to the connection requests.

Form an industrial (practical) point of view, impairment aware network planning (i.e., offline IA-RWA algorithms) should target the following important goals:

- Optimization of the resources (e.g., minimization of the number of wavelengths used to establish a given demand set). This feature allows network operator to choose lightpaths so that the links are underutilized (in terms of used wavelengths), and thus leave room for additional lightpaths to be established in the future.
- If blocking probability is not zero, and some connections are blocked, it is possible to estimate the extra resources (such as fibres, number of wavelengths and regenerators) that are required in order to route all the requested connections.
- The incorporation of physical impairments in an offline routing algorithm brings a further advantage through the joint optimization of physical layer impairments. This feature improves the signal quality of each lightpath (avoiding lightpath interference), leading to lower physical-layer blocking probability, and furthermore allows future connections to be established with

> higher probability, because the already established lightpaths have optimal or near optimal signal quality. It is important to underline that once a connection is established, rerouting is highly undesirable process, since it involves tearing down the previous lightpath, re-executing the algorithm and establishing a new lightpath, which would interrupt the service of the connection and possible affect the quality of service exhibited by the end users. Usually, rerouting is only allowed in a failure event.

The offline RWA problem is particularly interesting from a network designing perspective, since a good designed RWA algorithm can optimize the resources (e.g., minimize the number of wavelengths used to establish the requested connections), and also leave room for serving future connections. The incorporation of physical impairments in an offline routing algorithms permits cross-layer optimization, improving the signal quality of the lightpaths (avoid lightpath interference), leading to lower physical-layer blocking probability, and also allowing future connections to be established with higher probability because the already established lightpaths have an optimal or near optimal signal quality.

Offline algorithms are usually time-consuming, since the RWA problem (even without physical impairments or even if routing and wavelength assignment processes are considered separately) has been shown to be NP-Complete. Although it is not necessary for offline algorithms to have low running times, as it is for online algorithms, large scale experiments can be intractable. Finally, the performance of offline Rahyab, as an engine for re-routing the demands due to the failure in the network, was demonstrated.

Chapter 5:

5. Impairment-Aware Network Operation

Next generation optical networks are evolving from opaque to optical-bypass (translucent) and eventually to transparent (all-optical) networks [BSB$^+$08], [STL08]. The transparency in next generation optical networks enables signals to propagate from source to destination purely in the optical domain, eliminating current expensive electronic regenerators. This evolution paves the way for the construction of the required infrastructure for emerging data-intensive applications in a cost-effective manner [TAA$^+$08]. Despite those advantages, transparency in all-optical networks also introduces new issues in relation to the lack of electrical conversion as well as the still immature all-optical regeneration (e.g., 2R, 3R) technology. Since optical signals go directly through all-optical nodes (instead of costly electrical regenerators), physical layer impairments accumulate along a lightpath and also vary dynamically with the network state or configuration, potentially causing signals' quality of transmission (QoT), measured for instance in terms of Bit-Error Rate (BER) to drop beyond a predefined threshold. One way to mitigate physical impairments at network operation time is to use network-layer mechanisms, such as online Routing and Wavelength Assignment (RWA) algorithms, to assign lightpaths (a lightpath is the combination of a route and a wavelength) accounting for physical layer parameters, leading to the design of Impairment Aware RWA (IA-RWA) algorithms, which have recently received a lot of attention from the research community.

In this section the novel online IA-RWA algorithm will be presented, which is formulated as a multi-constraint IA-RWA problem. In the proposed approach the cost of a link is a vector (and not a scalar) with entries being the individual link impairments and other link parameters. This conceptual approach allows a different and more efficient handling of the impairments. Link and path constraints are the two types of QoS constraints considered. Link constraints specify the restrictions on the use of the individual links, while path constraints focus on the end-to-end QoS attributes of the entire path. In the multi-constraint case, each network link has multiple weights, which can be classified as additive, multiplicative or concave. For additive weights, the end-to-end weight of the path is the sum of the individual link weights. Delay is an example of an additive weight. A multiplicative path weight is the product of the link values along the path. Path reliability is an example of a multiplicative weight. Bandwidth belongs to the class of concave weights, since it involves the minimization operation (recall that the bandwidth of a path is the minimum of the bandwidths of the paths that comprise it). Since it is possible to transform the multiplicative case into the additive case by taking logarithms, cases with several additive constraints are only considered. Hence, the Multi-Constraint Path (MCP) problem can be defined as a routing problem, trying to find a path that satisfies a number of (additive) constraints.

Multi-constraint algorithms have been used for QoS routing problems in general wired networks [WC96], [CN98], [Jaf84], [KK01], [MK04], [WC96], [YL01], but not in particular in optical networks. Finding paths subject to two or more cost parameters/constraints is in most cases an NP-complete problem [GJ79], [MK03], [WC96]. For example, using a Depth-First Search (DFS) it is possible to find a feasible multi-constraint path, if one exists, but its worst case time complexity is exponential [SCS01]. As a result, most algorithms proposed in this area concentrate on solving the Multi-Constraint Path (MCP) problem or the Multi-Constraint Optimal Path (MCOP) problem in a heuristic and approximate way with polynomial and pseudo-polynomial-time complexities. The MCOP problem is a type of MCP, which tries to find a feasible optimal path using an appropriate cost parameter that is associated with each link and path.

In the multi-constraint IA-RWA algorithm presented in this chapter an MCP engine with a single mixed metric is utilized, instead of dealing with multiple link weights. Using a single mixed metric can reduce the algorithmic complexity, since a single source single destination shortest path algorithm such as Dijkstra can be employed. On the other hand, when a single mixed metric is used for routing, some information is lost [Jaf84], [KK01], [CFD01] in the sense that the mixed metric does not contain sufficient information alone to determine if QoS requirements are satisfied.

The TAMCRA algorithm presented in [NM98] uses a single metric and a k-shortest path algorithm in order to solve an MCP problem. The k-shortest path algorithms are able to find multiple paths between a given source and a given destination. This method reduces the performance shortcomings of using a mixed metric. The H_MCOP algorithm presented in [KK01] uses mixed metrics and is used for solving a MCOP problem.

The algorithms presented in [GM99], [JSM+01], and [FMP+01] also use a mixed weight for the link costs. These algorithms employ a Lagrange Relaxation method and try to find the best value for a weighting parameter (called ‘a’ in the algorithm description), and then apply Dijkstra’s algorithm in order to find a feasible path. These methods, however, need multiple runs of Dijkstra’s algorithm in order to find a proper value for the aforementioned parameter a. Yuan and Liu in [YL01] use a different definition of an optimal QoS path. They present an extended version of the Bellman–Ford Algorithm to find all the optimal (according to their definition) QoS paths between a source and a destination. Then a feasible path is selected if one exists.

A multi-constraint approach for the RWA problem in optical networks is presented in [JF04], with cost parameters being the OSNR, the number of free wavelengths, and the link cost. However, important parameters such as the interference among the channels are neglected in the OSNR approach adopted in that work. The proposed approach sends control packets over candidate paths that acquire cost-related information at the intermediate nodes, while the final choice of the lightpath is performed at the destination. In the proposed IA-RWA algorithm the single mixed metric MCP algorithm is exploited, defined in [KST+04], as the MCP engine of the proposed dynamic IA-RWA algorithm.

5.1 Multi-Constraint Path Framework

A network can be represented by a directed or undirected graph $G=(V, E)$, where V is the set of nodes (vertices) and E is the set of links (edges). In our routing problem, a path must be constructed between a specific source node and a destination node. It is assumed that the network graph is connected, in the sense that there exists at least one path between each pair of nodes in the network. For a certain source S, and destination D, let Π_{SD} be the set of all paths between S and D. The multi-constraint path problem (abbreviated MCP) can then be formulated as follows:

Definition 1: Consider a network topology, $G=(V, E)$, a source node S and a destination node D. Also, assume that each link $(i, j) \in E$ is characterized by M additive non-negative weights, $w_m(i, j), m=1,2,...,M$. Given constraints $C_m,\ m=1,2,...,M$, the MCP problem is to find a path $p \in \Pi_{SD}$, such that:

$$\sum_{(i,j)\in p} w_m(i, j) \leq C_m(i, j); m=1,2,...,M \ . \tag{5-1}$$

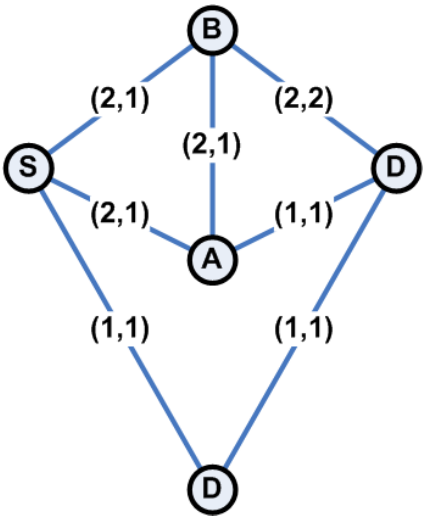
In order to clarify the MCP framework, an example is shown in Figure 5-1 (a), which is reported in [KST08]. Consider the network topology illustrated in part (a) of this figure. Each link of this network is characterized by two additive weights (cost parameters). Five different paths exist between the source node S and the destination node D, which are illustrated in Figure 5-1(b) together with their corresponding weights. Figure 5-1(c) shows the representation of these paths on the 2-dimensional plane, where each axis corresponds to a different weight. Constraints C_1 and C_2 are shown as straight lines parallel to the w_1 and w_2 axes. It can be seen from this figure that paths p_1 and p_5 are feasible since they satisfy the given constraints. In the graphical representation, feasible paths must be located inside the shaded rectangular region. This region is called the feasible region.

To address in an approximate way the M-constraint MCP problem, the single mixed metric $W_\lambda(p)$ for a path p is defined as:

$$W_d(p) = \sum_{j=1}^{M} \left(\frac{W_j}{C_j} \right)^d ; d \geq 1, \tag{5-2}$$

where W_j is defined as the sum of all additive costs of each link along the path:

$$W_j = \sum_{i=1}^{n} w_j(i)\,, \tag{5-3}$$

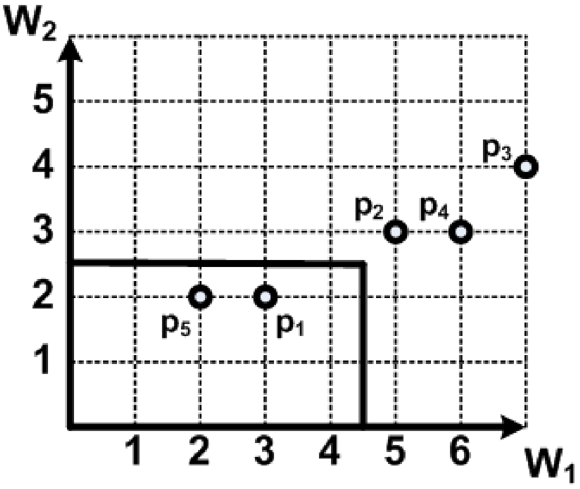


(a)

Path	W_1	W_2
p_1:(S,A,D)	3	2
p_2:(S,B,D)	4	3
p_3:(S,A,B,D)	6	4
p_4:(S,B,A,D)	5	3
p_5:(S,E,D)	2	2

$C_1=4.5$, $C_2=2.5$

(b)



(c)

Figure 5-1: Illustration of the multi-constraint path problem (MCP): a) Network topology, b) Path costs and constraints, and c) Solutions and feasible region.

and *n* is the number of links (hops) on path *p*. For the two-constraint problem, the following mixed metric was introduced in [Jaf84] for link *e*:

$$w(e) = d_1 w_1(e) + d_2 w_2(e)\,, \qquad (5\text{-}4)$$

where $w_1(e)$ and $w_2(e)$ are the two metrics associated with link *e* in the MCP problem, d_1 and d_2 are two constants and $w(e)$ is the single mixed metric associated with link *e*. This formulation is known as Jaffe's method. Figure 5-2 shows what may happen when the two constraints of the original MCP problem are replaced by a single constraint on the mixed metric. In particular, it depicts a case where paths *t* and *q* exist between the source and destination nodes. Path *t* is a feasible path since it satisfies C_1 and C_2 constraints. On the other hand, path *q* minimizes the mixed metric but is not a feasible path. This indicates that when the multiple constraints of the MCP problem are replaced by constraints on the mixed weights, the feasible solutions of the one problem are not necessarily the same with those of the other problem.

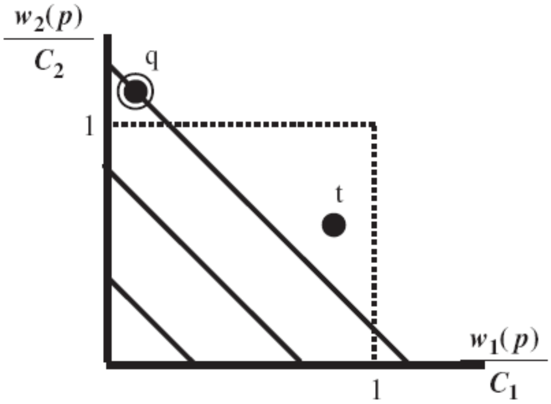


Figure 5-2: A feasible path exists but is not found [KST08].

It is proved in [KST08] that normalized weights of path *t* are more close to each other than the normalized weights of the infeasible path *q*. Figure 5-3 depicts an example of the relative position of the normalized weights. The same results are obtained for larger values of *d*, where *d* is the power of the polynomial summation as defined in Equation (4-2).

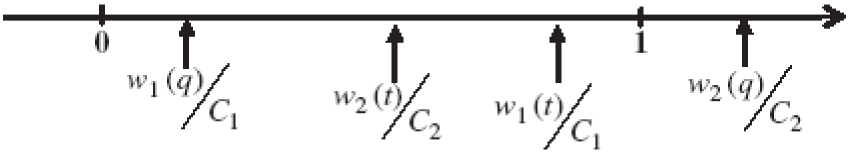


Figure 5-3: Relative position of the normalized weights of the paths t and q

This MCP framework is detailed in [KST$^+$04] and [KST08], which transforms the MCP problem to an (approximate) problem involving a new single mixed metric. Thus, our routing strategy should select a path that minimizes the mentioned single metric. Let:

$$\mu_\lambda(e)=\frac{1}{K}\sum_{i=1}^{K}\left(\frac{w_i(e)}{C_i}\right)^\lambda, \tag{5-5}$$

$$\Delta_{\lambda}(e)=\sum_{i=1}^{K}\left[\left(\frac{w_i(e)}{C_i}\right)^{\lambda}-\mu_{\lambda}(e)\right]^2, \qquad (5\text{-}6)$$

$$G_{\lambda}(e)=\mu_{\lambda}(p)\left[\Delta_{\lambda}(e)+\varepsilon\right];\ 0\le\varepsilon\le 1. \qquad (5\text{-}7)$$

The single metric that is going to be used in the proposed framework is defined in Equation (5-7). This relation considers the impact of both mean and variance of normalized weights in a single mixed metric. The contribution of mean (as defined in Equation (5-5)) is controlled with parameter ε.

The novelty of our approach and framework compared to the one reported in the mentioned references is the exploitation of the single-cost metric for *k*-shortest path or diverse *k*-shortest path algorithms. In other words, authors in [KST$^+$04] and [KST08] have simply modified the Dijkstra algorithm to find a single path between the source and destination node, while as it will be explained in the propsed algorithm, the MCP framework is utilized based on a single mixed metric for computing a couple of candidate paths between source and destination nodes, for a dynamic demand. This strategy could be based on the well-known Dijkstra shortest path algorithm. Furthermore, this MCP engine is exploited for diverse routing (e.g., the Bhandari algorithm) for protection purposes (e.g., 1+1) or generic *k*-shortest path algorithms. In the next sections the link cost vector are defined and the contributed IA-RWA algorithm is presented.

5.2 Link cost vector

In this sub-section the elements of the link cost vector that will be fed to the MCP engine are defined. Although, there is no particular limit for the number of constraints that can be utilized, in our proposed algorithm three constraints as the link cost parameters are being considered. These three metrics are: 1) Physical Link Length, 2) Polarization Mode Dispersion (PMD), and 3) Static Q-factor.

The first cost parameter in the multicost vector is the physical length of the link (PLL). The rationale behind this cost value is the tendency towards selecting shortest length paths. Also some of the static impairments (e.g., PMD) are directly related to the length of the links along the path. Therefore the goal of the MCP framework is to select lightpaths that have length less than a maximum optical reach (i.e., 2500km) [Sim05].

The second element of our cost vector is the PMD constraint. PMD management requires the time-average differential time delay Δt between two orthogonal states of the polarization, to be less than a fraction α of the bit duration $T=\frac{1}{B}$, where *B* is the bit rate. The PMD parameter for typical fibre lies between 0.5 and 2 $ps/\sqrt{km}$. However, carefully constructed new fibres can have PMD as low as

0.05 to 0.1 $ps/\sqrt{km}$. A typical value that can be used for the fraction α is 0.1 (10%). Assume that the transparent segment consist of M fibre spans, where the k^{th} span has length $L(k)$, and fibre PMD parameter $D_{PMD}(k)$. The constraint on the average differential delay can be expressed as:

$$B\sqrt{\sum_{k=1}^{M} D^2{}_{PMD}(k)\times L(k)} < \alpha . \qquad (5\text{-}8)$$

In addition to the physical link length and the PMD parameters, a static Q-factor estimation is also considered. By the term ‘static’ we refer to the impairments of such as ASE, PMD and Filter concatenation effects that do not depend on the utilization of the network (For more information about physical layer impairments please refer to Chapter 3). Therefore, for each link the variances of the static impairments are considered and the additive property is utilized to calculate the variance of the path by summing the variances of the links that comprise it. The main idea here is to consider the static physical impairments inside the multi-constraint path computation engine in order to prune out paths that do not satisfy the minimum QoT requirements (as far as the static physical impairments are concerned).

5.3 Online Rahyab

After introducing the building blocks of the contributed algorithm, in this section the functionality of our novel algorithm, named online Rahyab is presented. The flow chart of online Rahyab algorithm is depicted in Figure 5-4. Online Rahyab is a multi-constraint algorithm that utilizes a MCP framework that maps the link cost vector to a single mixed cost metric.

Upon the arrival of a permanent or limited-time connection request (a tuple of source, destination, number of requested lightpaths, and possibly duration), the current network topology is decomposed to W layers (wavelength planes), where W is the total number of available wavelengths in each fibre. For each wavelength plane, the candidate paths from source to destination using our MCP framework are computed. Therefore, the multi-constraint routing engine is exploited for finding paths that satisfy multiple constraints. These candidate paths correspond to a set of candidate lightpaths, based on the wavelength planes each path belongs to. This way the candidate lightpaths also conform to the wavelength availability constraint.

The next step is to construct another set of lightpaths, which is called the ‘useable’ lightpaths. In particular, each candidate lightpath is temporarily added to the currently established lightpaths set and the impact of this addition on the overall QoT (i.e., the QoT of all established lightpaths up to current time) is computed. If all QoT values are above a certain threshold (in the experiments this threshold was set to 15.5 dB, corresponding to a BER of 10^{-9}) the candidate lightpath under consideration will be moved to the ‘useable’ lightpath set. In this step, a simplified QoT estimator and the variances of the static noises represent the link costs. The final step of online Rahyab algorithm is to select the best useable lightpath. In order to find this lightpath, the one that introduces the minimum impact on the currently established lightpaths (,which is also utilized in offline Rahyab algorithm) is selected. In the case the 'useable' set is empty, the demand will be blocked. In this step the Q-Tool (ver. 2.21) is used as the QoT estimator. The flow diagram of the online Rahyab algorithm is shown in Figure 5-5.

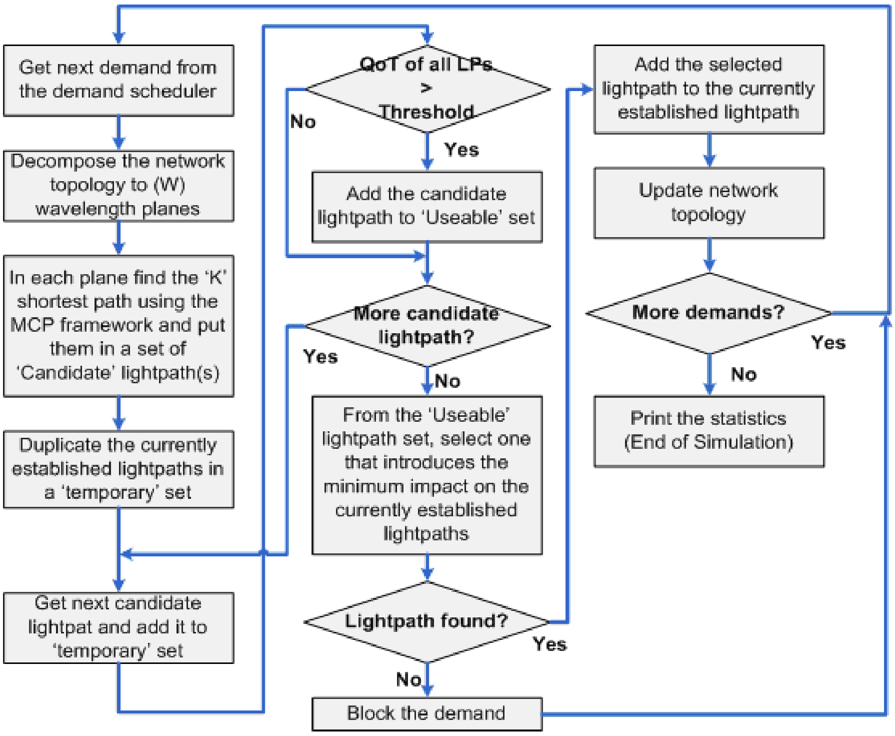


Figure 5-4: Flow chart of online Rahyab.

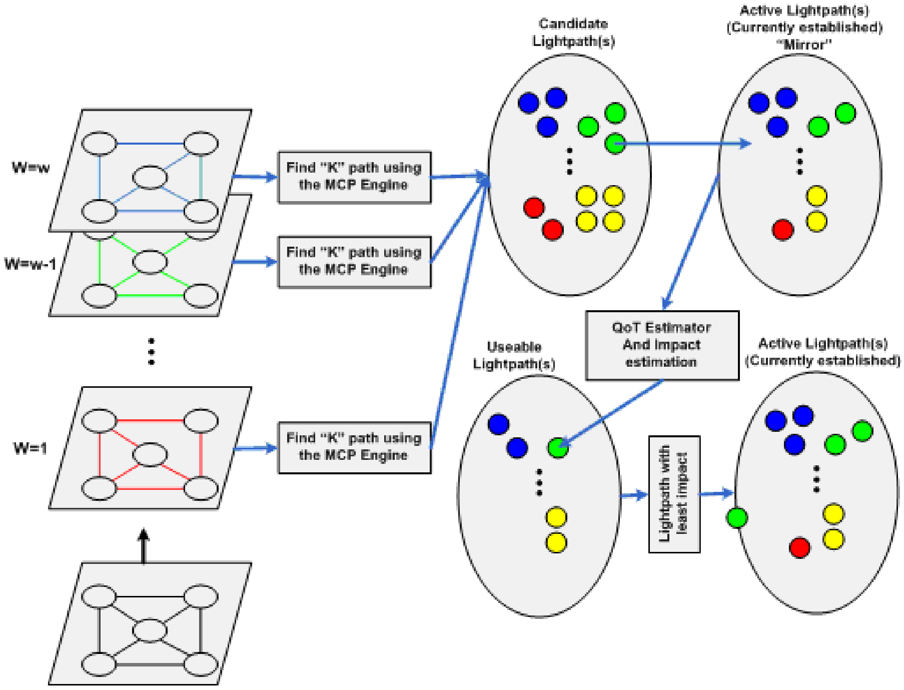


Figure 5-5: Flow diagram of online Rahyab.

The performance of the online Rahyab algorithm is evaluated in next section, where it is compared with the performance of the other online IA-RWA algorithms proposed in [CMK09].

5.4 Performance Evaluation of online Rahyab

In this section the performance of the online IA-RWA algorithms for transparent networks that were introduced in [CMK09] are compared. In order to fairly compare the algorithms, a number of simulation experiments with controlled and identical input parameters and an identical impairment estimation module (Q-Tool version 2.21, as defined in Chapter 3) were performed. The parameters and the set of experiments were chosen so as to obtain a broad range of results that would reveal the relative performance of the algorithms and their applicability under diverse scenarios. The algorithms that are compared in this section are the following [CMK09]:

- The Sigma-Bound multicost algorithm using the MUW optimization function and by rerouting established connections when needed, coded as SB_MUW.
- The Sigma-Bound multicost algorithm using the Mixed optimization function. In this comparison this algorithm will be referred to as SB_Mixed.
- The Multi-Parametric multicost algorithm using the minTP optimization function. In this comparison this algorithm will be referred to as MP.
- The Rahyab multi-constraint algorithm that was presented in Section 5.3. In our joint experiments it is assumed that three shortest paths will be computed for each connection request (*k*=3). It is also assumed that the optimal optical reach is 2500 km.
- The *k*-SP-Q (*k*=3) algorithm as defined and presented in [CMK09].

To summarize some of the key characteristics of the compared algorithms, the SB_Mixed, the SB_MUW and the MP schemes are based on the multicost approach. In the multicost approach a vector of cost parameters, which are related to different impairments or QoS parameters, is assigned to each link. Then, by defining appropriate operations between these cost parameters, the cost vector of a path is calculated. These algorithms produce a number of candidate lightpaths for each connection request, and an optimization function is applied to their cost vectors so as to select one of them. The SB_Mixed and SB_MUW algorithms differ in the optimization function applied, Mixed vs. MUW as defined in [CMK09]. The SB_* and the MP algorithms differ mainly in the definition of the parameters of the links' and paths' cost vectors. The SB_* class of algorithms includes certain parameters in its cost vectors (calculated through appropriate models of the impairments) that directly take into account the Q-factor of the lightpaths, while the MP class of algorithms take the physical impairments indirectly into account, by using various impairment generating sources parameters [CMK09] The *k*-SP-Q selects the shortest available route among the *k* shortest routes in distance; the First Fit wavelength assignment scheme is utilized for selecting the wavelength; and finally this algorithm checks the QoT value of the selected lightpath.

The joint experiments were conducted in the framework of Work Package WP4.2 of DICONET project. The network topology that was chosen for these joint experiments is the generic DTNet topology (Defined in Appendix A) consisting of 14 nodes and 23 edges (46 directional links).

All experiments were performed using the same dynamic demand set (traffic matrix) Connection requests (each requiring bandwidth equal to 10Gbps) are generated according to a Poisson process with rate λ (requests/time unit). The source and destination of a connection are uniformly chosen among the nodes of the network. Two traffic scenarios are considered: i) the “arrivals only” scenario, where connection durations are taken to be infinite and ii) the “arrivals and departures” scenario, where connections have a finite duration. The duration of a connection is given by an exponential random variable with average $1/\mu$ (time units).

The “arrivals only” scenario models well the actual situation for many telecom operator networks, which only experience increasing traffic between source and destination nodes (usually cities) of their core networks, and a lightpath that is set up, almost never terminates (unless some failure occurs). The “arrivals and departures” scenario is used to model traffic in the projected future networks, where lightpaths will be more dynamic than they are today, and they will be set up and torn down “on demand”. An online IA-RWA algorithm that performs well under the “arrivals and departures” scenario is expected to also perform well under the “arrivals only” scenario. This is why most of the works reported in the literature on online RWA or IA-RWA algorithms assume the “arrivals and departures” scenario when evaluating the performance of the algorithms.

For the “arrivals only” scenario 20 traffic files were created with $\lambda=1$ request/time unit, using each time a different seed for the Poisson process generator. In our graphs the values measured using these traffic files are averaged. For the “arrivals and departures” scenario seven traffic files were creatred with different λ/μ ratios, measured in Erlangs (80, 100, 120, 140, 160, 180, 200 Erlangs). In both scenarios connections arrive one by one, and should be served, if possible, upon their arrival. This means that the algorithm cannot wait to collect more than one connection and serve them jointly. The order of the arrivals is important and connections are treated as they arrive (in a First Come First Served - FCFS basis). In each experiment 1000 connections were created and served.

To compare the algorithms the following performance metrics are used:

- Connections served until the first blocking occurs (applies only to the “arrivals only” scenario): The number of connections that are served until the first blocking occurs are counted. It is assumed that the executed algorithm tries only once to serve a connection. If the connection is blocked, then the algorithm is not re-executed.
- Blocking rate (applies only to the “arrivals and departures” scenario): The blocking rate is the ratio of the number of blocked lightpath requests over the total number of requested lightpaths. Blocking rate is expressed in percent.

For example if in total 10000 connection demands were considered and 50 of them were blocked then the blocking rate is (50/10000) = 0.5%. It is assumed that the executed algorithm tries only once to serve a connection. If the connection is blocked, then the algorithm is not re-executed.

- Average running time per connection: This is the average time required by the algorithm in order to serve one connection (either accepted or not). If the algorithm calls many times the Q-Tool then the running time should also include the running time of Q-Tool. Also, if the algorithm performs re-routing, the average running time for serving a connection, also includes the time it takes to perform the re-routing.
- Relative average running time per connection: Since it is difficult to provide the same hardware/software platform for all involved partners to compare the running time of their algorithms, the relative running time performance metric can be defined. The required time for network load=100 Erlangs can be considered as the unit of running time and the running time of other loads can be expressed in terms of this unit.
- Relative average number of lightpaths that follow the shortest path: The number of chosen lightpaths that use the shortest hop path are counted. Assuming 1000 connection demands, of which 800 have used the shortest path, the relative average number of lightpaths that follow the shortest path is 80%.

Although, the experiments were performed with identical inputs, they were executed on different personal computers (PCs). So for completeness, in the following table the specifications of the PCs and the software that were used in the experiments are provided.

Table 5-1: Characteristics of the simulation platforms [CMK09]

Algorithm	CPU/Memory	Operating System	Software used
SB_RWA	Intel Core2 Duo @3.GHz 4 GB RAM	Windows Vista 32bit	MATLAB R2008a
MP_RWA	Intel Xeon L5420 @ 2.5Ghz (4 Core) 8GB RAM	Windows Server 2008 (Standard) 64-bit	MATLAB R2008b
Rahyab	Intel Xeon L5420 @ 2.5Ghz, 1GB RAM[1]	Windows XP Professional, SP3	MATLAB R2007a, Microsoft Visual C++ 6.0
k-SP (proposed in the literature)	Intel (R) Pentium (R) D @3.GHz 1GB RAM	Windows XP Professional	MATLAB R2007a, Microsoft Visual C++ 6.0

5.4.1 Arrivals and Departures traffic scenario

The performance of the 3-SP-Q, SB_Mixed, SB_MUW, MP and online Rahyab IA-RWA algorithms under dynamic traffic, where the incoming connection requests are processed one by one and are either served (by finding and establishing a

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1 - VMWare workstation 6.5.2 was used to clone multiple instances of the virtual machines to perform the simulations in parallel. The specification of the host machine is as follows: Hardware:Intel Xeon L5420 @ 2.5GHz, and 8GB RAM Software: Microsoft Windows Server 2008, SP1

lightpath) or blocked, is presented in this section. Through this set of experiments the algorithms' performance are evaluated, assuming that connection blocking is an acceptable operation in the network and as a result the interest is in minimizing its occurrence. The results are presented as a function of the number of available wavelengths, for fixed network load (equal to 100 Erlangs).

Figure 5-6 shows the blocking rate of the evaluated algorithms. The SB_MUW and the Rahyab algorithms produce the best results, while the 3-SP-Q algorithm is the worst. Also, the SB_Mixed and the MP algorithms' performance are very close to eachother. As expected, the number of connections blocked decreases as the number of available wavelengths increases, and most of the algorithms reach to zero blocking in the end. In all cases, most connections are blocked mainly due to physical impairments, since the network load is relatively small (100 Erlangs). The MP algorithm takes indirectly into account the impairments and as result its performance is worse than that of the other algorithms that directly consider the physical impairments [CMK09]. All the results are presented as a function of the number of available wavelengths, for fixed network load (equal to 100 Erlangs).

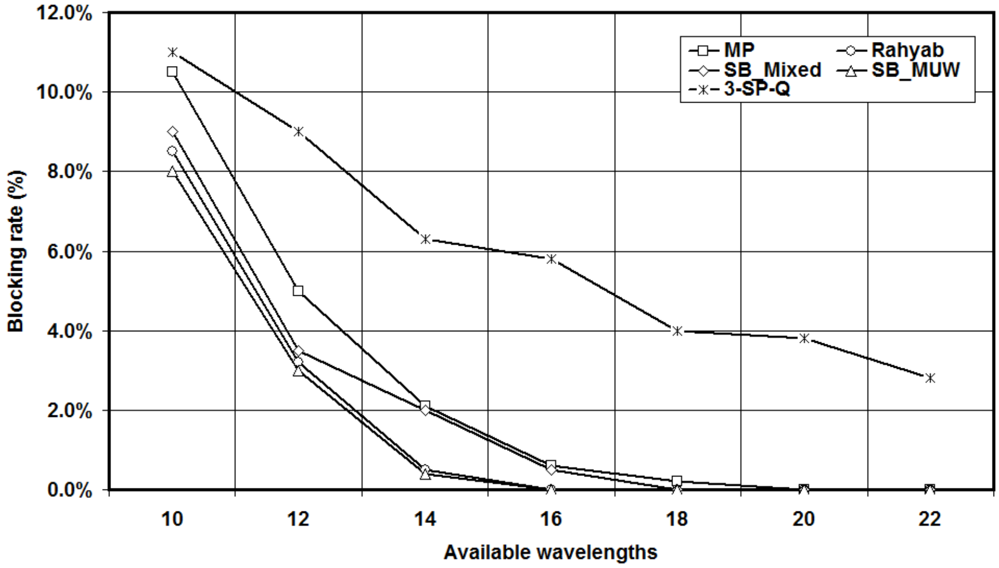


Figure 5-6: Blocking rate vs. number of available channels per link.

In Figure 5-7, it is observed that the execution time (which is depicted in logarithmic scale) of the Rahyab algorithm is very large, while those of the other multicost algorithms are quite smaller. The main reason for this behaviour is that the Rahyab algorithm invokes the Q-Tool intensively for selecting among the 'useable' set lightpaths, the one that introduces the minimum impact on the currently established lightpaths. On the other hand the multicost algorithms employ the Q-Tool only in the end, so as to accept or reject/block the decided lightpath. Also, it is observed in Figure 5-7 that the execution times of all the algorithms increase with the number of available wavelengths, since in this case fewer connections are blocked and the Q-Tool has to take into account a larger number of established lightpaths during its operation. The SB_MUW algorithm uses the rerouting operation, so as to reroute established connections whose QoT deteriorates due to the establishment of new connections. However, this operation does not seem to increase significantly the SB_MUW algorithm's execution time [CMK09].

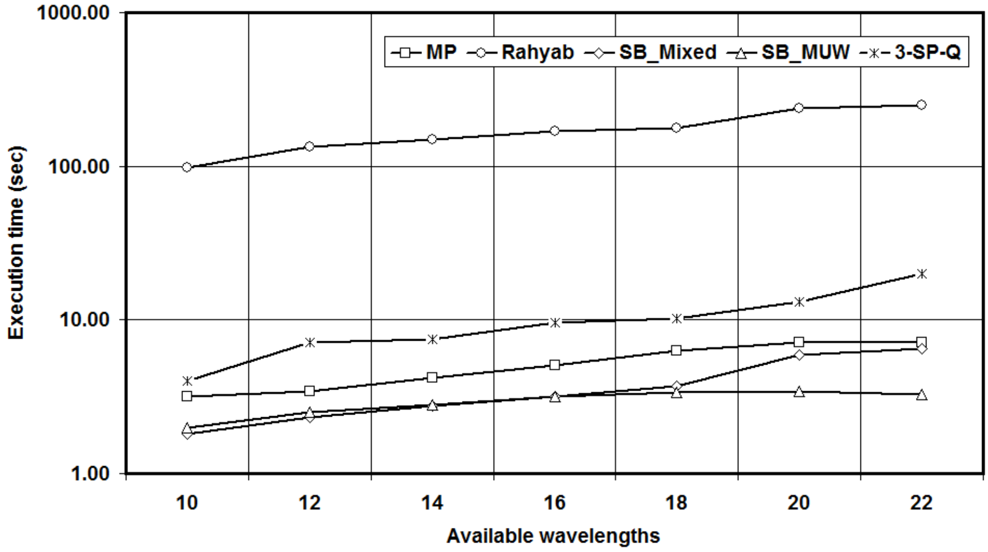


Figure 5-7: Execution time vs. number of channels per links.

Figure 5-8 illustrates the percentage of lightpaths selected that follow the shortest path. It is observed that for all algorithms, with the exception of the 3-SP-Q, this percentage is between 55% and 75%. Also, the 3-SP-Q algorithm always (100%) selects the shortest path when sufficient wavelengths are available. This percentage increases initially along with the number of wavelength, and then remains constant. Even though this percentage can be considered high (for all the algorithms), the IA-RWA algorithms do not only select the path to be followed but also the wavelength to be used, and does so under the wavelength continuity constraint.

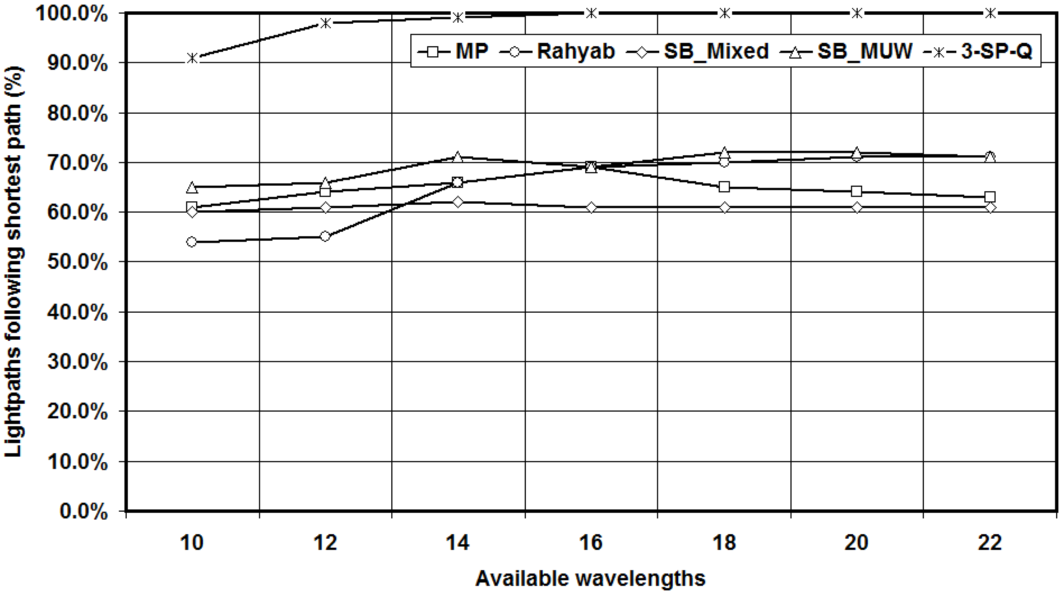


Figure 5-8: The percentage of selected lightpaths using the shortest path.

In Figure 5-9 the performance of the 3-SP-Q, SB_Mixed, SB_MUW, MP and online Rahyab IA-RWA algorithms are compared as a function of the network load, for a fixed number of wavelengths (*W*=20). The increase of the network load, as expected, deteriorates the algorithm's performance, just as the performance of the algorithms deteriorates when the number of wavelengths is reduced. In particular, the SB_MUW and the Rahyab algorithms result in the smallest blocking probability, while the SB_Mixed and the MP algorithms' blocking probabilities are higher. Also, the Rahyab algorithm has the largest execution time, due to the intensive invocation to the Q-Tool. For all the algorithms, with the exception of the 3-SP-Q, the percentage of lightpaths selected that follow the shortest path is between 60% and 80%.

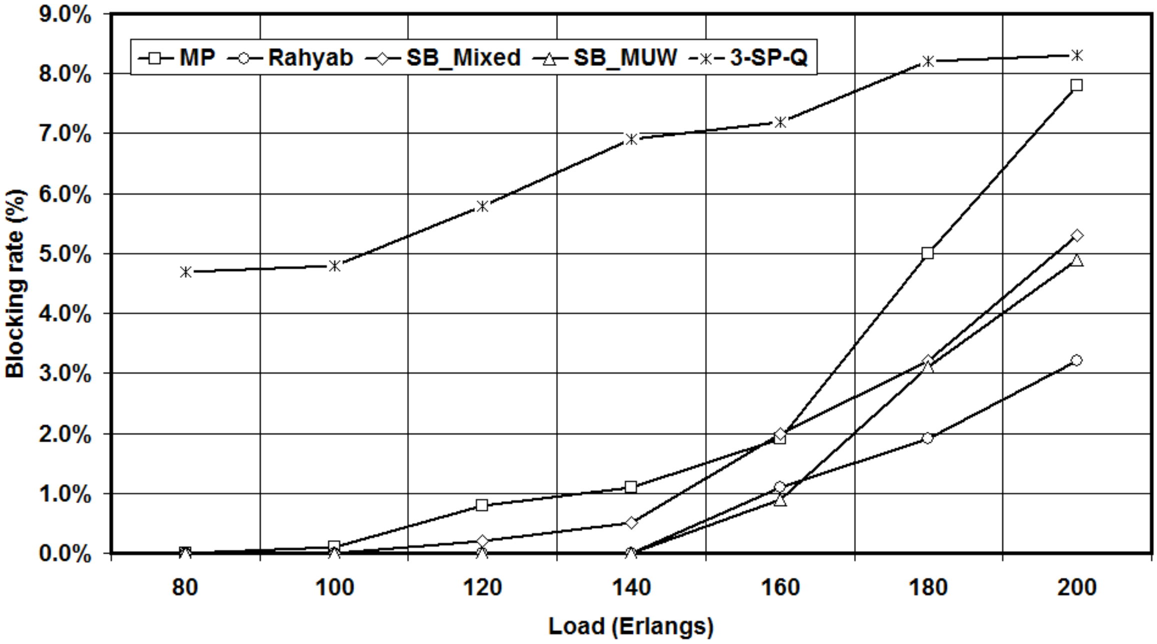


Figure 5-9: Blocking rate vs. load in the network

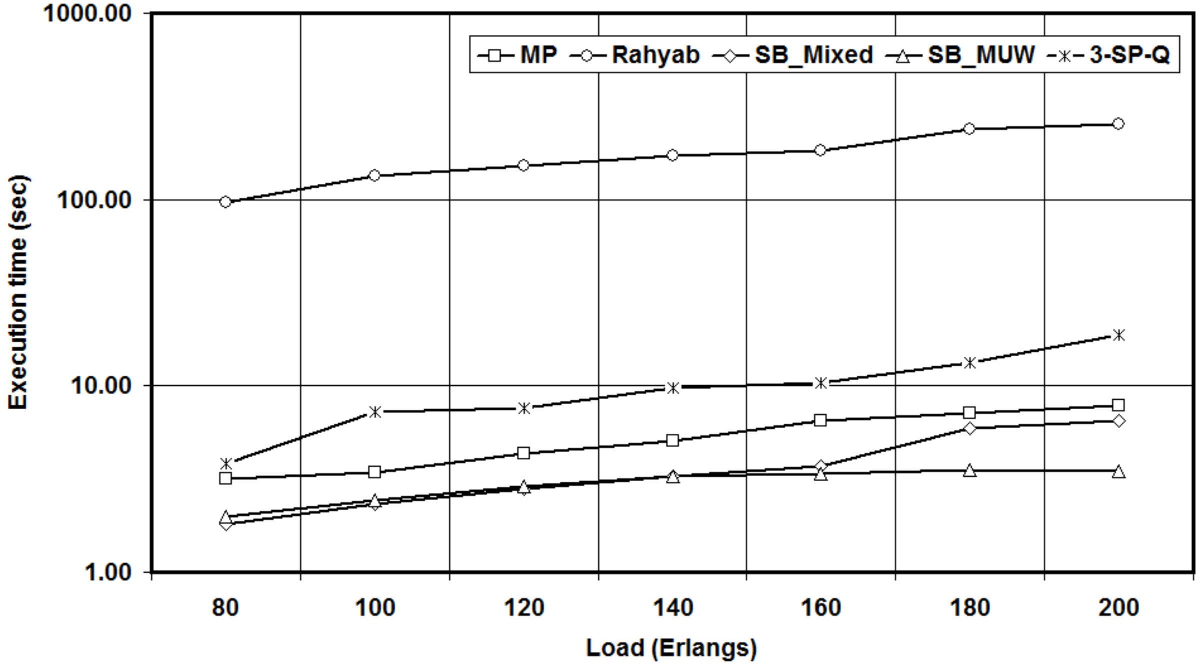


Figure 5-10: Execution time vs. load.

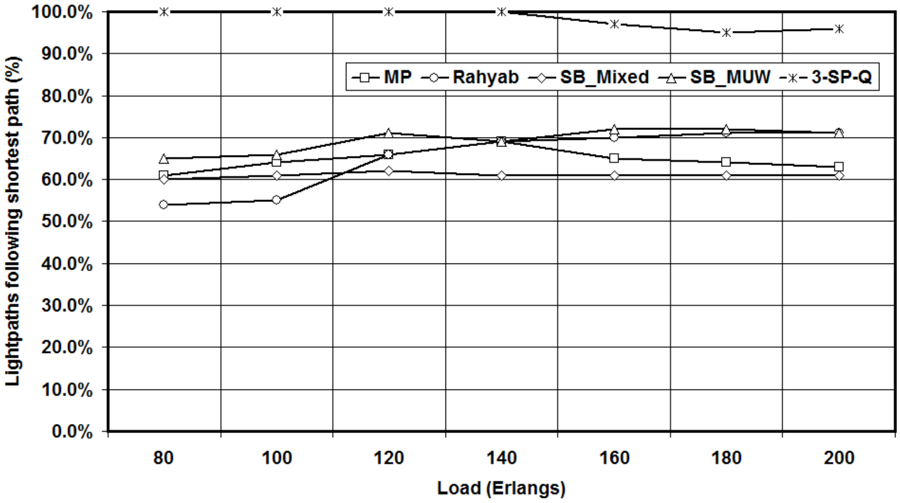


Figure 5-11: The percentage of selected lightpaths following the shortest path.

5.4.2 'Arrivals Only' Traffic Scenario

The performance of the 3-SP-Q, the SB_Mixed, SB_MUW, MP and online Rahyab IA-RWA algorithms under dynamic traffic, where an experiment starts with an empty network and is stopped when the first connection is blocked is compiled in this sub-section. Through this set of experiments the performance of algorithms are evaluated assuming that connection blocking is not an acceptable operation [CMK09].

In Figure 5-12 it is observed that the SB_MUW is able to serve more connections than the other algorithms before the first blocking occurs. The SB_MUW is followed in terms of performance by the Rahyab, the SB_Mixed, the MP and the 3-SP-Q algorithms. All algorithms are able to serve more connections as the number of available wavelengths increases and that the differences between the algorithms become then more evident. In the "arrivals only" traffic scenario, in contrast to the "arrivals and departures" scenario, the 3-SP-Q algorithm's blocking performance is close to the one achieved by the SB_Mixed and the MP algorithms. This is because the network is initially lightly loaded and as a result the shortest path is in many cases a good candidate path for the requested connection.

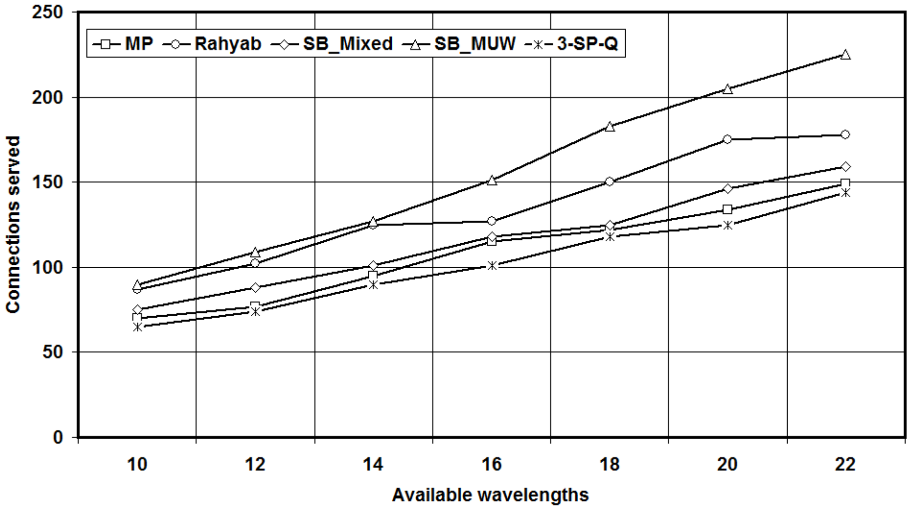


Figure 5-12: Served connections vs. number of channels per fibre links.

5.4.3 Performance Evaluation Summary

In this sub-section the performance of four different online IA-RWA algorithms are compared: Sigma-Bound, Multi-Parametric, online Rahyab and 3-SP-Q, under common scenarios, QoT estimator and network topology. For the Sigma-Bound algorithm the Most Used Wavelength (MUW) with re-routing were used and the Mixed optimization functions (Mxed), while for the Multi-Parametric the minTP optimization function was utilized. The online Rahyab algorithm has a good blocking rate performance; however its execution time is very large. The main reason for this behaviour is that the Rahyab algorithm uses the Q-Tool at its intermediate steps to select among the set of 'useable' (candidate) lightpaths, the one that introduces the minimum impact on the currently established lightpaths. The performance of online Rahyab algorithm can be considerably improved by accelerating the performance of the Q-Tool (e.g., using FPGA hardware acceleration).

5.5 Inaccuracy of QoT estimation

One of the key building blocks in IA-RWA algorithms is a QoT estimator, which is a combination of theoretical models and/or interpolations of measurements, typically performed offline (in the lab, before the networks is deployed), but also possibly online. A practical QoT estimator should be fast to ensure that lightpaths can be established in real time. In addition, models by nature cannot capture all effects actually present in physical systems, resulting in QoT estimation inaccuracies. Inaccuracies are inevitable yet undesirable for two reasons: on the one hand, if the QoT of a candidate lightpath is estimated as acceptable while it is not, then a lightpath is established while it should not. Eventually a monitor (such as a BER monitor integrated in the receiver) will catch the problem and the lightpath will be torn down and re-establishment will be requested, wasting resources used by the failed lightpath, and time. On the other hand, if the QoT of a candidate lightpath is estimated as unacceptable while QoT is actually acceptable, then the IA-RWA algorithm will have to seek a new candidate for the lightpath, likely less optimal (e.g., consuming more resources) than the first candidate, hence again wasting resources and time. A practical IA-RWA algorithm should mitigate the inaccuracies due to QoT estimation in order to eliminate the occurrence of both cases to the maximum possible extent. Note that the problem of incorporating QoT estimation inaccuracies in the dimensioning of transparent optical networks was tackled in [ZML$^+$08], where the authors studied the amount of regeneration devices needed to compensate for the additional QoT margin incurred by the inaccuracy of a QoT (Q-factor) estimator; in [ZML$^+$08] the problem of the impact of the RWA technique on the network dimensioning was left out.

In this section, a variation of online Rahyab is proposed to address such inaccuracies directly within the decision steps of the IA-RWA algorithm in order to mitigate them and eliminate the occurrences of both cases described above to the maximum possible extent. A novel IA-RWA algorithm that considers the availability of Optical Impairment Monitoring (OIM) or Optical Performance Monitoring (OPM) [KBB$^+$04] equipment to alleviate the inaccuracy of QoT estimations is presented here. Monitor equipment availability is mapped to QoT accuracy and is taken into account within a multi-constraint framework as a new constraint (the other constraint being a traditional QoT-related one), at the routing step of a proposed Routing and Wavelength Assignment heuristic. Doing so ensures that routes where monitors are available are preferred over routes with less monitoring capability, consequently increasing the accuracy of the QoT estimator and reducing the aforementioned issues associated with inaccurate QoT estimators. Our novel heuristic algorithm, called "Online Rahyab", outperforms state-of-the-art IA-RWA algorithms under the same assumptions for common metrics such as blocking rate and resource utilization.

5.5.1 Inaccuracy of Q-Tool

Practical QoT estimators including our Q-Tool are combinations of analytical models and/or interpolations of measurements and simulations. For instance in [LYT$^+$08] the authors propose a method to measure more accurately OSNR on transmission lines at the expense of the deployment of additional power monitors. However, and this is particularly true in highly dynamic transparent optical networks, practical QoT estimators should be fast in order to support quick lightpath establishment.

As mentioned above the errors resulting from incorrect QoT estimation have a direct impact on lightpath establishment decisions, yet physical models are by nature imperfect and optimization for speed is further detrimental to their intrinsic accuracy. The trade-off between availability of monitoring information, and monitoring accuracy are formalized here. In our framework a lightpath with estimated Q-factor $\hat{Q}$ by the Q-Tool is established if and only if $\hat{Q}$ is larger than a given threshold $Q_{\text{Thereshold}}$ (e.g., $Q_{\text{Thereshold}}$ = 15:5 dB to achieve BER=10^{-9} without Forward Error Correction, FEC), to which a margin $\eta Q_{EM}\,;(0 \le \eta \le 1)$ is added:

$$\hat{Q} > Q_{Threshold} + \eta Q_{EM}\ . \tag{5-9}$$

In (4-9), the Q_{EM} parameter is the maximum error (inaccuracy) that the Q-Tool estimator can introduce and η is a factor that depends on the availability of the additional monitoring information.

As an illustrative example, assume that a network operator is running a network and injects traffic until sustaining a first call blocking. This call blocking can be due to either lack of resources (wavelength blocking) or QoT insufficiency (QoT blocking). This is done for a 14-node national network similar to that operated by Deutsche Telekom (see Appendix A for full details). The number of established lightpaths is given for $Q_{Threshold}$ =15.5 dB, Q_{EM} =0.5 dB, and for the two extreme values of η: η = 0, corresponding to the case where full confidence in the Q-factor estimation is guaranteed and it returns the true Q-factor of a lightpath (possibly because some monitors are deployed, that greatly improve the Q-Tool accuracy), and η=1, corresponding to the case with maximum inaccuracy of the Q-Tool. It is seen in Figure 5-13 that a higher confidence in the estimate of Q or, alternatively, a lower value of η, permits to postpone the point in time when the first blocking occurs; for a system with 10 channels 40% more lightpaths can be accommodated if high confidence in the Q estimates (η = 0) is achieved, compared with the case where this confidence is not feasible/available (η = 1). However, this difference is reduced to

2% when the number of channels per fibre is increased to 22. The reason for this reduction is that the availability of more wavelengths increases the chance of finding a lightpath that satisfies the (higher) required threshold. This framework enables us to place some constraint on the adaptive error factor η in order to force the routing engine to find paths with more accurate QoT estimation. It can be observed that even a small inaccuracy in QoT estimation (e.g., 0.5 dB) can dramatically change the performance of the call admission procedure. In the example above, η is set to a fixed value; however, it is clear from the example that gains in call admission performance are expected if η can be lowered.

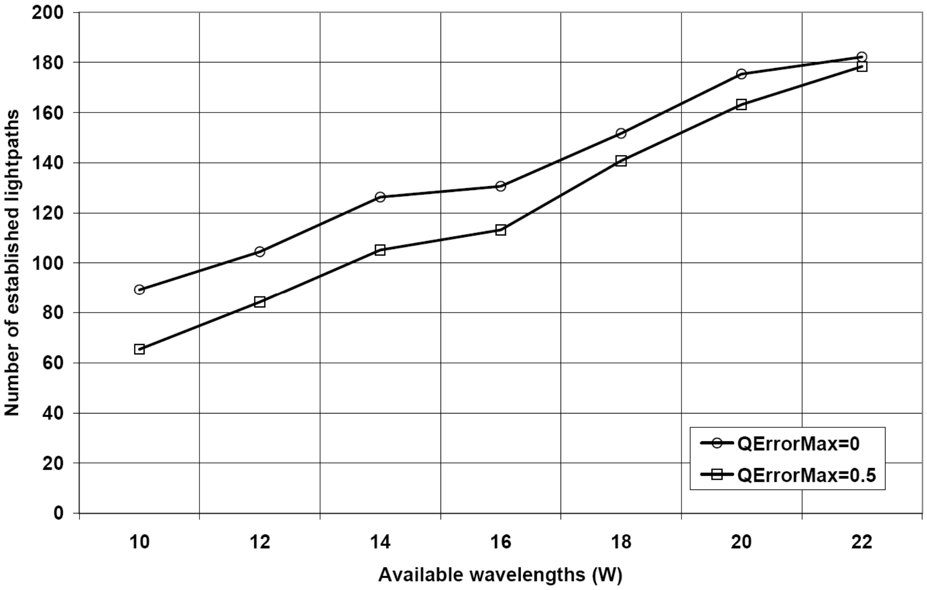


Figure 5-13: Number of established lightpaths until the occurrence of first blocking as a function of available wavelengths per fibre for two values of Q_{EM}.

We propose to account for OIM/OPM availability information dynamically, on a per-route basis, in order to compute the true value of η for each lightpath to be established, and hence to reduce the blockings due to too high margin on $\hat{Q}$ whenever that is possible using an appropriate, novel IA-RWA algorithm.

5.5.2 Online Rahyab Variation

In Chapter 1 of this Ph.D. thesis a comprehensive survey of IA-RWA algorithms were provided, and here the conclusions of [AKM$^+$09] is simply used to choose suitable candidates to compare our new IA-RWA algorithm with. Note that no IA-RWA algorithms so far have accounted for Q-factor estimation inaccuracy, and hence the algorithms presented here assume a constant margin ηQ_{EM}. The following two algorithms were selected because of their performance in terms of average blocking rate in fully transparent optical networks. The K-SP-Q algorithm is described in [YSR05]. This algorithm selects the shortest available route among the *K* routes between each source and destination pair, which are pre-computed as the *K* shortest paths; the First-Fit wavelength assignment scheme is utilized; and finally these algorithms checks the quality of transmission (QoT) value.

The MmQ (Max Min Q-factor) algorithm is described in [PBS$^+$08]. In MmQ algorithm for each wavelength, a route from source to destination is computed subject to the wavelength continuity constraint. Then, for each of the computed lightpaths, the QoT values of that candidate lightpath and already established lightpaths are computed. Lightpaths with value of Q lower than a given threshold, or lightpaths that interfere with other lightpaths so as to produce a value of Q for them lower than the threshold are discarded. From the list of previously computed lightpaths that are not discarded, the one with the highest QoT value is finally selected. In addition to low blocking, the algorithm has some desirable properties such as high fairness between short and long lightpaths.

The main idea behind the online Rahyab algorithm is to design a multi-constraint IA-RWA algorithm that considers QoT accuracy through optical monitor (i.e., OIM/OPM) availability information in routing decisions, in order to alleviate the inaccuracy of the QoT estimator (here, Q-Tool). Our multiconstraint IA-RWA maps several constraints, including QoT itself, and QoT inaccuracy, to a single cost metric using the MCP framework (See Section 4.1).

In this variation of online Rahyab algorithm two metrics are considered as the link cost parameters: lightpath length, and Q-Tool inaccuracy margin.

- **Lightpath lengths**: Capping the length of a lightpath is a quick and easy way to disregard candidate lightpaths with poor QoT; indeed, considering only static impairments, i.e., impairments that do not depend on the network state: ASE noise, PMD and filter concatenation, one can compute the maximum length $L_{\max}$ of a lightpath such that the QoT constraint is met. Lightpaths longer than $L_{\max}$ are known for sure to have an unacceptable QoT; note that the converse does not hold, as lightpaths shorter than $L_{\max}$ may also have an unacceptable QoT when dynamic effects (XPM, FWM) are accounted for. The main idea here is to consider the static physical impairments inside the multi-constraint path computation engine in order to prune out paths that do not satisfy the minimum QoT requirements (as far as the static physical impairments are concerned).
- **QoT estimator inaccuracy**: The second metric is the Q-Tool inaccuracy. The optical monitor availability vector is defined as a binary vector that records whether a particular monitor is available on a link or not, where each m_k is associated to the presence ($m_k = 1$) or absence ($m_k = 0$) of a monitor (for instance, OSNR monitor, PMD monitor, residual chromatic dispersion monitor, channel wavelength monitor, etc.) on a given link. In order to map the monitor availability vector of link e to a single value the function Θ is defined as follows:

$$\Theta(e) = \sum_{k=1}^{n} \varepsilon_k(e)\left(1 - m_k(e)\right), \qquad (5\text{-}10)$$

In (5-10) the sum is indexed by the monitors and it is assumed that n different monitors for each link e can be used. The parameter ε_i determines the importance of the i^{th} monitor. More specifically, considering the estimated Q-factor $\hat{Q}$ as a random variable that differs from the true Q-factor of a lightpath depending on what monitoring information is available to perform the estimation, $\Theta(e)$ is interpreted as the variance of $\hat{Q}$ due to the uncertainty of parameters on link *e*, and each $\varepsilon_i(e)$ as the contribution to the variance of $\hat{Q}$ due to the absence of monitor *i* on link *e*. The adaptive factor η for a lightpath *p* introduced in (5-9) can be re-interpreted as:

$$\eta(p) = \frac{\sum_{e \in P} \Theta(e)}{\Theta_{\max}(p)} \tag{5-11}$$

where $\sum_{e \in P} \Theta(e)$ is the variance of $\hat{Q}$ accounting for uncertainties stemming from the presence/absence of monitors on each link of the considered lightpath, and $\Theta_{\max}(p)$ is the maximum variance for the lightpath. This maximum uncertainty corresponds to the absence of monitors on a lightpath. The constraint corresponding to this QoT uncertainty metric is then:

$$\eta(p) < \eta_{\max}\ , \tag{5-12}$$

where $\eta_{\max}$ drives the maximum uncertainty ($\eta_{\max} Q_{EM}$) that the network manager is willing to tolerate in the network, or, equivalently, the minimum amount of monitoring that must be present on a path for a lightpath to be established.

This variation of online Rahyab is escribed here. In online Rahyab each link is associated with a single weight we, which mixes the two metrics “link length” and “QoT estimator uncertainty”, using (5-7). Upon the arrival of a connection request between a source and a destination node, the current network topology is decomposed into *W* layers (wavelength planes), where *W* is the total number of channels in each fibre. For each wavelength plane, a predefined number *k* of candidate paths are computed from source to destination using a shortest path algorithm considering a single cost metric, which includes link length constraint and QoT estimator uncertainty constraint.

Therefore, the multi-constraint routing engine is exploited for finding paths (denoted by candidate lightpaths) that satisfy multiple constraints. Doing so separately for each wavelength ensures that the candidate lightpaths also conform to the wavelength continuity constraint. Once candidate lightpaths are determined, another set of lightpaths are constructed, and called the usable lightpaths: each candidate lightpath is temporarily added to the currently established lightpaths in the network and the impact of this addition on the QoT of each lightpath already established is computed. If all QoT values are above a certain threshold the candidate lightpath under consideration will be moved to the usable lightpath set. In this step, the Q-Tool (version 2.21) is used that considers all important physical impairments as defined in Chapter 3. The final step of proposed algorithm is to select the best usable lightpath. In order to find this lightpath, the candidate lightpath that introduces the minimum impact on the currently established lightpaths (as defined in section 5.3) is selected. In the case where the usable set is empty, the demand is blocked.

5.5.3 Comparative studies

In order to provide a fair comparison between the algorithms, simulation studies were performed with controlled and identical input parameters and an identical impairment estimation module (Q-Tool). The parameters and the set of experiments were chosen so as to obtain a broad range of results that would reveal the relative performance of the algorithms and their applicability under diverse scenarios. In addition to online Rahyab, the performance of the K-SP-Q and MmQ algorithms were also evaluated, which were briefly described in Section 5.5.2.

The network topology in our simulation studies is DTNet (See Appendix A for more details). This network has 14 nodes and 23 bidirectional links, with an average node degree of 3.29. The line rate in this network is assumed to be 10 Gbps. A heterogeneous network topology is assumed in which the node and link architectures have different impact and contributions on the physical layer impairments. It is also assumed that pre-dispersion compensation of 400 ps/nm is performed in the links. The Standard Single Mode Fibre (SSMF) length in each link is set to 100 km, followed by a Dispersion Compensation Fibre (DCF) that under-compensates the dispersion of the preceding SSMF by a value of 30 ps/nm/km. At the end of each link the accumulated dispersion is fully compensated. It was assumed that the SSMF fibres have a dispersion parameter of 17 ps/nm/km and attenuation of 0.25 db/km. The DCF segments have a dispersion parameter of 80 ps/nm/km and an attenuation of 0.5 dB/km. The input power to the links is -4 dBm and 3 dBm per channel in the DCF and SSMF fibres respectively. The channel spacing is set to 50 GHz. The noise figure of the amplifiers that compensate for the loss of the preceding fibre segment is set to NF#6 dB, with small variations. The signal-to-crosstalk ratio in nodes is set around -32 dB, with small variations in each node. The threshold value for computing the impact on Q-factor (i.e., $Q_{Threshold}$) is 15.5dB, corresponding to BER=10^{-9} without FEC.

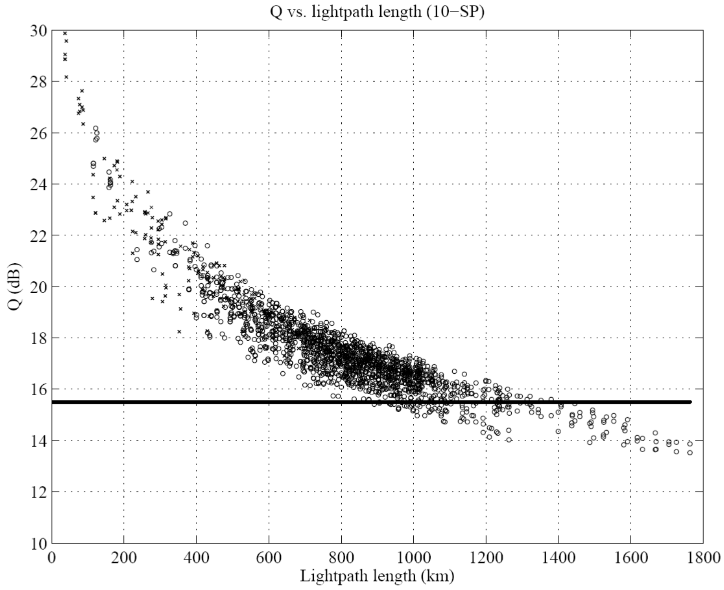


Figure 5-14: Q-Factor value vs. lightpath length ($Q_{Thereshold}$ = 15:5 dB).

In Figure 5-14, the Q-factor value for all 10 shortest paths between all possible pairs of the nodes in the network is depicted, totalling 1820 lightpaths. Without considering the impact of other established lightpaths, the maximum optical reach is about 1500 km, hence let $L_{\max}$ = 1500 km. Similarly let $\eta_{\max}$ = 0.9 in constraint (5-12).

Connection requests (dynamic demand set) are generated according to a Poisson process with rate λ (requests/time unit). The source and destination of a connection are uniformly chosen among the nodes of the network. The duration of a connection is given by an exponential random variable with average $1/\mu$. The ratio λ/μ is varied, which measures in Erlangs, the total offered load to the network. Connection requests arrive one by one, and should be served upon their arrival. This means that the algorithm cannot wait to collect more than one connection and serve them jointly. In each experiment, 1000 connections were created and served.

In the K-SP-Q algorithm, the value of K is set to 3. In the online Rahyab algorithm, The value of d and ε is set to 1 and 0:5 respectively in order to compute the single mixed cost for links. Online Rahyab algorithm sets the value of K to 5 for computing candidate routes.

5.5.4 Results

In order to evaluate the performance of different algorithms the following performance metrics were considered: the blocking rate for each demand set is the ratio of the number of blocked lightpath requests over the total number of requested lightpaths (this metric is reported for both different values of load and also number of channels per link), the number of required wavelengths in order to achieve 0% blocking rate for the given demand set, and the admissible load to the network to achieve 1% blocking rate for different monitor deployment scenarios.

These metrics are good indicators for network designers in order to perform network planning and dimensioning. Figure 5-15 depicts the performance of K-SP-Q, MmQ and our proposed online Rahyab algorithm ("Rahyab-100%"). In our experiments the performance of the algorithms is evaluated assuming that connection blocking is possible and as a result the interest is to minimize it. Note that there is no QoT inaccuracy consideration in K-SP-Q and MmQ and therefore their performance should be compared with Rahyab with full monitor deployment ("Rahyab-100%") that completely removes the inaccuracy of QoT estimation. The results are presented as a function of the number of channels per fibre, for a fixed network load (100 Erlangs).

In order to reveal the impact of the monitors on the performance of online Rahyab algorithm, the deployment rate of monitors in the network is varied between 0% and 100%. The results are depicted in Figure 5-16. The performance of the MmQ and K-SP-Q algorithms is also included for comparison purposes. The five variations of the Rahyab algorithm are denoted as Rahyab-0% to Rahyab-100% which correspond respectively to no or full OIM/OPM deployment in the network. For the case of 0% monitor deployment, it is assumed that Q_{EM} =1 dB as also considered in [ZML+08].

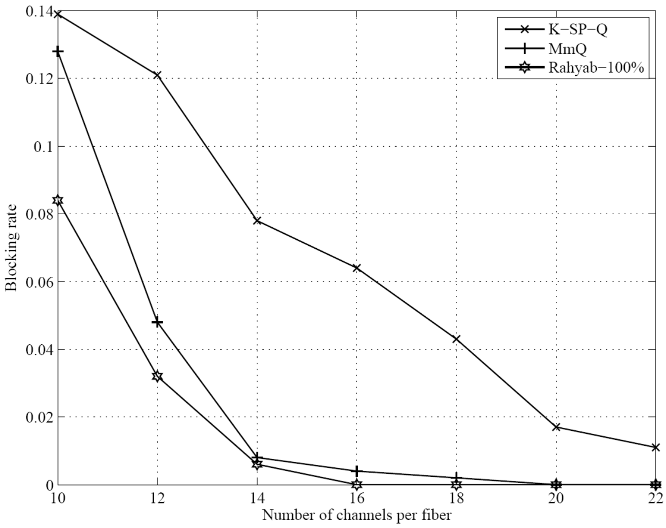


Figure 5-15: Blocking rate vs. number of channels per link, Load=100 Erlangs.

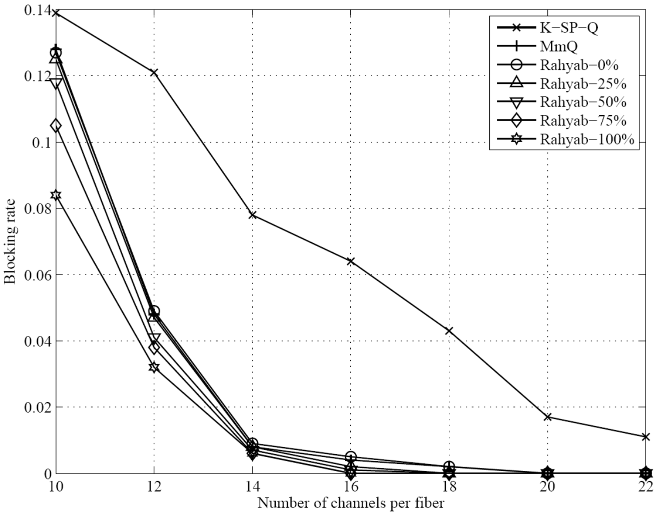


Figure 5-16: Blocking rate vs. number of channels per link, Load=100 Erlangs.

It can be observed that when there is no inaccuracy in QoT estimation (100% monitor deployment), the online Rahyab algorithm performs better than all other algorithms. Besides, by increasing the number of channels per fibre the blocking rate is decreased, since the chance of finding a route and available wavelength that satisfies the required QoT threshold increases. The performance of the MmQ algorithm that does not consider the inaccuracy of QoT estimation is almost similar to the performance of the Rahyab algorithm without any monitor deployment, i.e., 0% monitor deployment. The reason why online Rahyab algorithm performs better than the MmQ is mainly due to the availability of additional route options in online Rahyab compared to single shortest path in the MmQ algorithm. The K-SP-Q algorithm does not perform better, mainly due to the inability to properly incorporate the impact of physical impairments in its routing decisions.

By increasing the amount of OIM/OPM monitoring equipment, the online Rahyab MCP routing engine finds routes that compensate for the inaccuracy of the

QoT estimation, which is why the blocking rate decreases when the optical monitor deployment rate increases. However the difference between various deployment scenarios is more pronounced for lower numbers of channel per fibre. Indeed, by increasing the number of channels, finding proper route and available wavelength that satisfies the QoT requirement becomes easier. When the number of channels per link is set to 10, Rahyab-100% (with support of full OIM/OPM deployment) performs 51% better than the same algorithm in absence of any OIM/OPM monitor deployment (i.e., Rahyab-0%).

Figure 5-17 depicts the performance of the selected algorithms for different values of the network load and a fixed number of channels per link (i.e., *W*=20). The increase of the network load, as expected, deteriorates the performance of all algorithms, just as the performance of the algorithms deteriorates when the number of wavelengths is decreased. Among studied algorithms, Rahyab and MmQ perform better than K-SP-Q algorithm. In this figure five variations of the Rahyab algorithm are included to also consider the impact of OIM/OPM deployment. By increasing the number of deployed monitors, the Rahyab MCP engine finds routes with more available monitors that lead to lower inaccuracy of QoT estimation. Note that the inaccuracy of QoT estimation is only considered for online Rahyab algorithm (except Rahyab-100%) and other algorithms exploit a Q-Tool without any inaccuracy (i.e., QEM=0 dB). At the maximum load (200 Erlangs), the online Rahyab with full monitor deployment performs 53% better that online Rahyab without any monitor deployment.

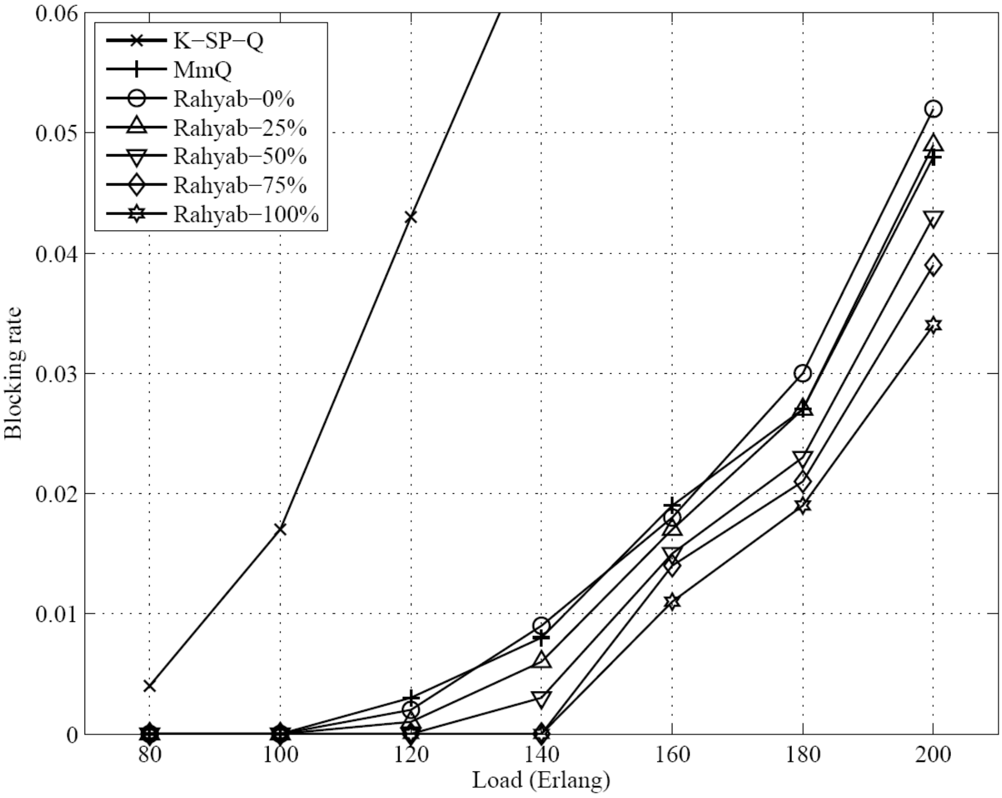


Figure 5-17: Blocking rate vs. load (W = 20).

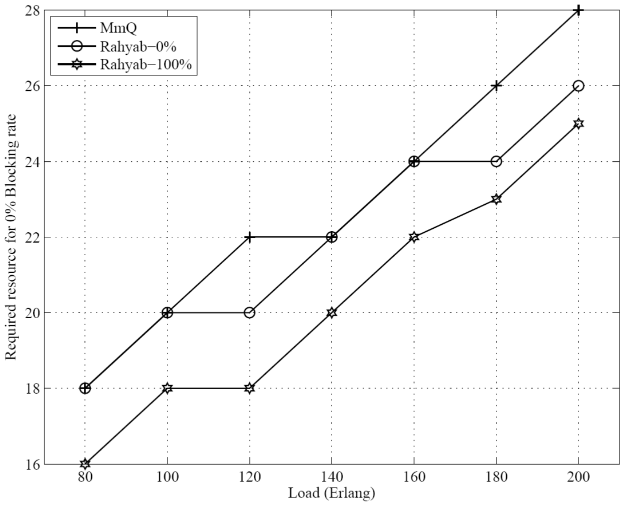


Figure 5-18: Number of required W for 0% blocking vs. load.

In Figure 5-19, the maximum admissible load is reported to achieve a blocking rate of 1%, when the amount of monitoring equipment deployment varies. With MmQ, monitoring deployment is only accounted for in the QoT condition via a varying Qth, i.e., $Q_{\text{Threshold}}$ = 15.5 dB for full monitoring deployment and $Q_{\text{Threshold}}$ = 16.5 dB for no monitoring deployment. “Rahyab” integrates monitoring deployment within the RWA decision and so benefits from the additional monitoring deployment better than MmQ, as can be seen with the increasing gap between the MmQ and “Rahyab” curves. When there is no monitor deployment in the network, the gap is amounted to only 6%, while by increasing the rate of monitor deployment the performance of Rahyab algorithm became better than MmQ algorithm by 11%. The MmQ algorithm has been also enhanced to consider the monitor deployment rate in its RWA decisions in the same way that Rahyab considers it, and as it can be observed the “enhanced” MmQ algorithm performs better than MmQ algorithm. However since the MmQ algorithm only computes a single path between the source and destination, its performance still remains lower than Rahyab algorithm.

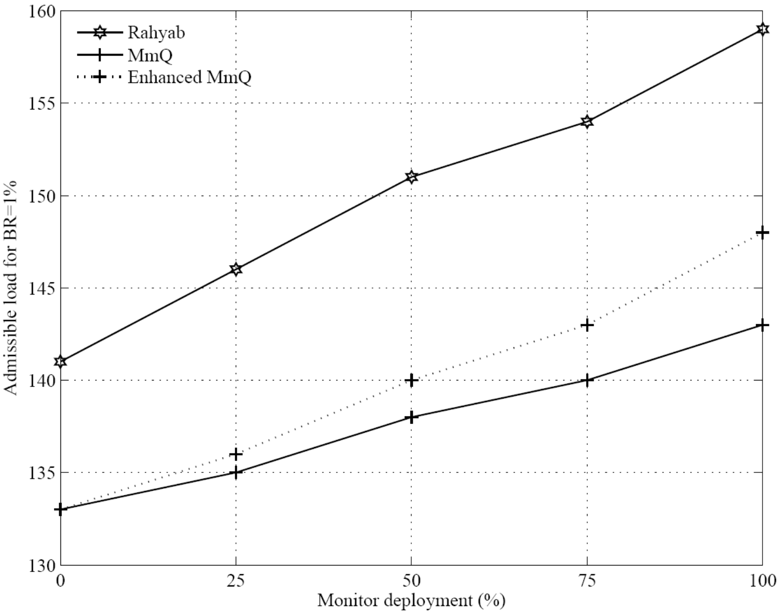


Figure 5-19: Admissible load to achieve 1% blocking rate.

5.6 Chapter Summary

The novel online IA-RWA algorithm (i.e., Online Rahyab) was presented in this Chapter. This algorithm utilizes a multi-constraint framework. The novelty of our approach and framework compared to the one reported in the mentioned references is the exploitation of the single-cost metric for *k*-shortest path or diverse *k*-shortest path algorithms. In other words, authors in [KST$^+$04] and [KST08] have simply modified the Dijkstra algorithm to find a single path between the source and destination node, while as explained the MCP framework based on a single mixed metric is used for computing a couple of candidate paths between source and destination nodes, for a dynamic demand. This strategy could be based on the well-known Dijkstra shortest path algorithm. Furthermore, this MCP engine can be exploited for diverse routing (e.g., the Bhandari algorithm) for protection purposes (e.g., 1+1) or generic k-shortest path algorithms.

In this chapter the performance of four different online IA-RWA algorithms: Sigma-Bound, Multi-Parametric, online Rahyab and 3-SP-Q, were considered under common scenarios, QoT estimator and network topology. For the Sigma-Bound algorithm the Most Used Wavelength (MUW) with re-routing and the Mixed optimization functions (Mxed) was used, while for the Multi-Parametric the minTP optimization function was utilized. The online Rahyab algorithm has a good blocking rate performance; however its execution time is very large. The main reason for this behaviour is that the Rahyab algorithm uses the Q-Tool at its intermediate steps to select among the set of ‘useable’ (candidate) lightpaths, the one that introduces the minimum impact on the currently established lightpaths. The performance of online Rahyab algorithm (with respect to its running time) can be considerably improved by accelerating the performance of the Q-Tool (e.g., using FPGA hardware acceleration).

A novel online IA-RWA algorithm, called “online Rahyab,” was also presented that considers the availability of the OIM/OPM monitors in the network within the routing and wavelength assignment process. Indeed, a fundamental aspect for an IA-RWA strategy in order to be actually implemented is to utilize Optical Impairment/Performance Monitoring (OIM/OPM) for evaluation of signal quality. In addition to the exploitation of monitoring information in IARWA engines, it is also useful to incorporate the availability of OIM/OPM monitors in QoT estimations (e.g., Q-Tool). It was shown that for a system with 10 channels per fibre, 40% more lightpaths can be accommodated if high confidence in the Q estimations is available compared with the case where high accuracy is not available. The performance of proposed algorithm is compared with two other algorithms that have been selected from state-of-the-art IA-RWA algorithms. The simulation results indicates that utilizing the optical monitors in the network can improve the performance of the IA-RWA algorithms by roughly more than 50% for high traffic load or limited number of channels. It was demonstrated that the admissible load for a given blocking rate is 11% higher than the one which is allocated by an algorithm that does not consider the OIM/OPM deployment in the network. It was also demonstrated that, due to the important impact of QoT estimator inaccuracies on network dimensioning (here, in terms of blocking rate), RWA algorithms need to incorporate those inaccuracies in order to appropriately reflect the actual behaviour of monitored transparent optical networks.

Chapter 6:

6. Network Planning and Operation Tool

The evolution trend of optical networks is a transformation towards higher capacity and lower costs core optical networks. The promise of future optical networks is the elimination of a significant amount of electronic equipment (lower CAPEX and OPEX), as well as added capabilities, such as the ability to transport any type of data format (modulation and bit rate independence) through the network [BSB$^+$08] and support for dynamic demands. As one of recent efforts toward this goal, the key outcome of the DICONET project is the design and development of an intelligent Network Planning and Operation Tool (NPOT), which consider the impact of physical layer impairments in planning and operation phase of optical networking.

Network planning is more focused on the details of how to accommodate the traffic that will be carried by the network. In this phase, which typically occurs before a network is deployed; there is generally a large set of demands to be processed at one time. Therefore the main emphasis of network planning is on finding the optimal strategy for accommodating the whole demand set (traffic matrix). In network operation phase the demands are generally processed upon their arrival and once at a time. It is assumed that the traffic must be accommodated using whatever equipment already deployed in the network. Therefore the planning process must take into account any constraint posed by the current state of the deployed equipment, which, for instance, may force a demand to be routed over a sub-optimal path.

In this Chapter an approach for design and development of DICONET NOPT and its key building blocks along with control plane integration schemes is presented. The modular design and development of NPOT paved the way for including some of the contributed algorithms of this Ph.D. study in this tool. The performance of Offline Rahyab (as one of the NPOT building blocks) is also presented here, which is compared with a similar tool provided by Alcatel-Lucent Bell Labs France.

6.1 NPOT Building Blocks

The main novelty of the DICONET project is the design and development of physical layer impairments aware NPOT that incorporates the performance of the optical layer into Impairment Aware Routing and Wavelength Assignment (IA-RWA), component placement, and failure localization algorithms. The NPOT is integrated into a unified extended Generalized Multi-Protocol Label Switching (GMPLS)-based control plane. The anatomy of the NPOT is depicted in Figure 6-1. Network Description repositories, QoT estimator, IA-RWA engines, Component placement modules and Failure localization module are the key building blocks of NPOT.

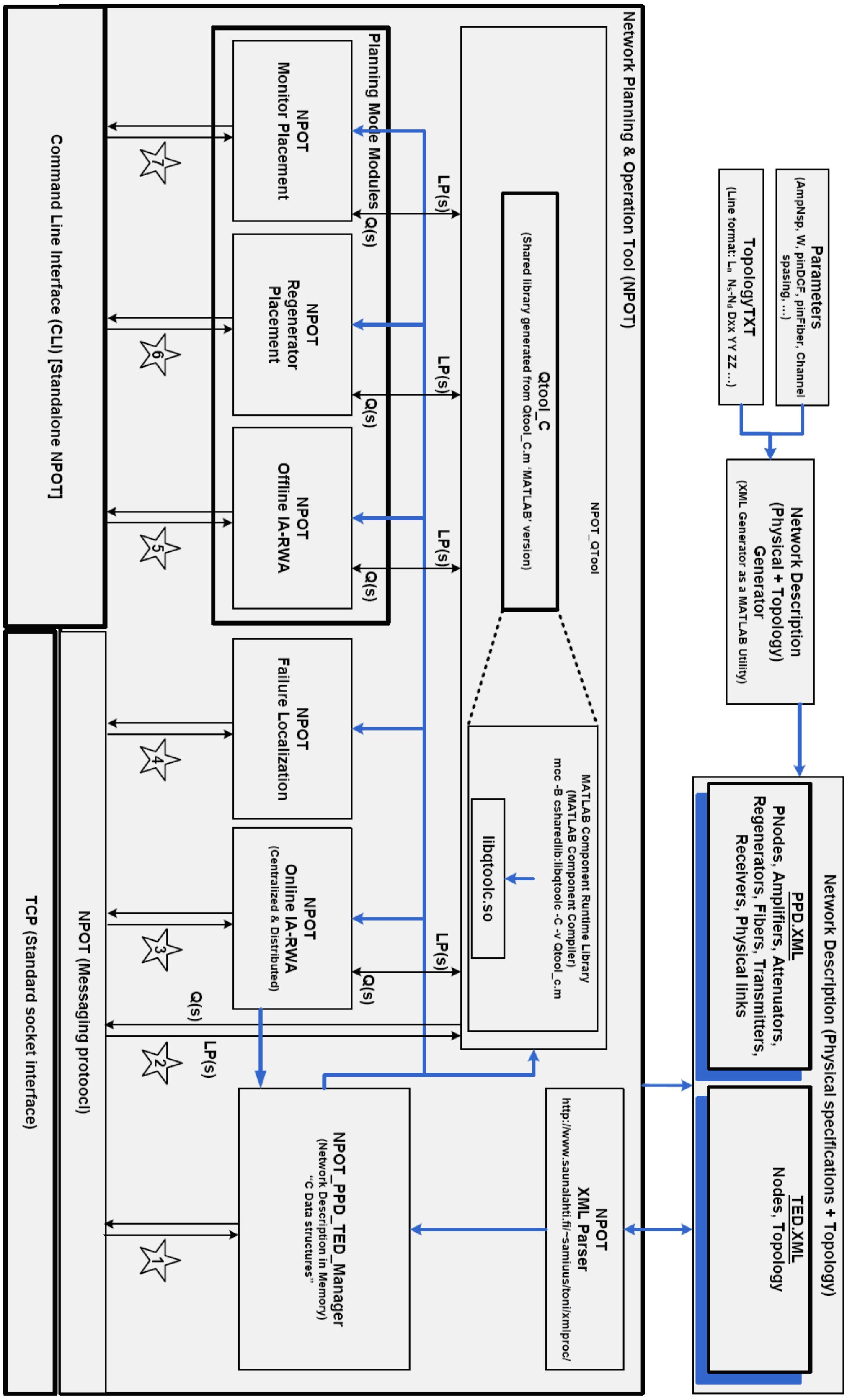


Figure 6-1: Anatomy of the DICONET NPOT.

The planning modules are accessible through a command line interface (CLI). In order to realize the communication of the NPOT with the other entities in the DICONET control plane integration scheme (operation mode), a messaging protocol layer is designed and implemented on top of the standard TCP/IP socket interface. In the sequel the details of each building blocks of NPOT is presented. In order to realize the DICONET vision, several building blocks should be considered in an orchestrated fashion.

6.1.1 Network Description Repositories

The network description (both in physical layer level and topology level) is included in two main data repositories that are kept as external files to NPOT. These two repositories are named PPD.XML and TED.XML. The Physical Parameters Database (PPD) is the master repository, which includes the lower-level XML files that define the physical characteristics of the links, nodes and components on the network links. More specifically, physical nodes, amplifiers, attenuators, fibres (both transmission fibres and DCF modules), transmitters and their related parameters, receivers and their related attributes and finally the definition of physical links are kept in various XML files and all of them are referenced in the PPD.XML. In fact PPD.XML plays the role of a master repository with pointers to other physical layer related XML files.

The other global data repository to NPOT is the Traffic Engineering Database (TED), which is implemented as another master repository named TED.XML. This repository includes the Nodes and Topology XMLs. These two repositories (i.e., Nodes and Topology) describe the network in more abstract and higher level. In fact the connectivity of the nodes and the definitions of network nodes (nodeID, node names,) are kept in Topology.XML and Nodes. XML repositories.

In order to facilitate the generation of PPD and TED related repositories, another module (external to NPOT) has been developed, which receives two main inputs (Topology.txt and Parameters) and generates the TED and PPD related XML files. This utility module is developed in MATLAB as presented in upper part of Figure 6-1. The “Parameters” is a MATLAB data structure that also controls the generation of PPD related XMLs. The important fields of this MATLAB data structure (i.e., Parameters) are:

- AmpNsp
- W (Number of channels per fibre)
- pinDCF (input power for DCF fibres)
- pinFibre (input power to transmission fibres) and
- ChannelSpacing

The “topology.TXT” is another input to the XML generator module that includes the definition of physical links, source and destination node and the components (mainly DCF fibres and transmission fibres) in the links. The XML Generator utility receives these two inputs and generates the various XML files that are defined in PPD.XML and TED.XML master repositories. However the network description as defined in these XML files can be more customized and tailored by editing the individual XML files and fine tuning particular parameters.

6.1.2 NPOT XML Parser

The NPOT_XML_Parser is the NPOT internal module that is responsible for parsing the XML repositories and transform the network description (physical specification and network topology) into the internal data structures (in C), which are kept inside the NPOT memory. An open source XML parser (http://www.saunalahti.fi/~samiuus/toni/xmlproc) has been used, which is available in ANSI C. This XML parser parses the PPD and TED related repositories and moves them to the corresponding C data structures.

6.1.3 PPD & TED Manager

The NPOT_PPD_TED_Manager is the module, which is responsible to manage the PPD and TED data structures as they are kept in the global memory of NPOT. This module also provides the interface to the first NPOT messaging protocol (indicated by star 1 in Figure 6-1). The NPOT messaging protocol layer is responsible for bridging the communication of NPOT to the outside entities. This messaging protocol layer is built on top of the standard TCP socket interface. The first messaging protocol paves the way for communication of the NPOT with outside entities, which are requesting to access (mainly update the PPD and/or TED) data structures. In addition to participating in this messaging protocol, the NPOT_PPD_TED_Manager provides the required input for other internal modules in the NPOT, so the other modules have access to the PPD related and TED (i.e., topology related) data.

6.1.4 NPOT Q-Tool

The NPOT_QTool is one of the key building blocks of the NPOT. This module provides the required access to the Q-Tool (version 3.33) functionality as the physical layer performance evaluator. The NPOT_QTool receives a set of lightpaths (at least one lightpath) and then computes the Q value of those lightpaths and return them back to the calling module. The Q-Tool is originally implemented using MATLAB development environment and in order to integrate it in the NPOT, the MATLAB Component Runtime library is utilized to generate a shared library from the MATLAB module and the NPOT_QTool invokes the shared library with proper parameters.

The communication of NPOT_QTool with other entities outside the NPOT is performed through messaging protocol 2. The general signature of NPOT_QTool is as follows:

int NPOT_QTool(Lightpaths *LP, unsigned int LPCount, QType* Q),

in which the LP is a pointer to the Lightpaths structure, LPCount determines the number of lightpaths that will be passed to NPOT_QTool and Q is a pointer to the returned value (the corresponding Q values of the lightpaths). The NPOT_QTool computes the Q value of each lightpath and returns it back to the calling module. Note that both LP and Q could be dynamically allocated and could have more than one lightpath. The NPOT_QTool function return value indicates that the whole Q computation was successful or not.

6.1.5 Online IA-RWA

The entities outside the NPOT invoke the NPOT_Online_IARWA module in order to get a lightpath (route or route and wavelength). The behaviour of NPOT_Online_IARWA is different in distributed and centralized control plane integration schemes.

- In the **distributed** integration scheme the NPOT_Online_IARWA upon receiving a demand, computes "*k*" routes from source to destination. In case of demand with (1+1) protection requirement, the NPOT_Online_IARWA computes "*k*" diverse pairs of primary and backup paths between source and destination. Then it responds back the number of found routes (which is not necessarily "*k*", if finding "*k*" paths was not feasible) and also returns the paths in the form of lightpath element data structure. Note that lightpath element includes both the primary and backup lightpaths. If demand is for a primary path only, then the backup lightpath related fields will be initialized to zero. The routes are expressed in node sequence. The caller (i.e., Optical Communication Controller 'OCC') tries to establish the lightpath from source to destination using the extended signalling protocol. If a lightpath (or a pair of lightpaths in case of 1+1 protection) is(are) established the OCC informs the NPOT_Online_IARWA of established lightpath (indicated by proper identification number assigned for lightpathid). Then NPOT updates the lightpath element global data structure (via TED & PPD manager) by adding the established lightpath to the list of active lightpaths and also updates the 'Topology' global data structure by removing the assigned channels from the occupancy field of 'Topology' data structure to indicate that assigned channel is no more available on the established path. If none of the "*k*" candidate routes are feasible, the caller (i.e., OCC) sends the proper status code back to the NPOT.
- In the **centralized** integration scheme the NPOT_Online_IARWA [KCM+09] computes the lightpath(s) from source to destination and assign wavelength for them and returns it (i.e., the computed lightpath) back to the caller (i.e., OCC). OCC tries to establish the lightpath using the signalling protocol and returns the result of the lightpath establishment back to the NPOT_Online_IARWA. If the establishment is successful, NPOT updates the active (established) lightpaths in the network and also updates the Topology global data structure. The assigned wavelengths will be removed from the occupancy field of 'Topology' for all links that are residing along the lightpath. If the lightpath establishment was not successful, OCC sends the status back to the NPOT_Online_IARWA.

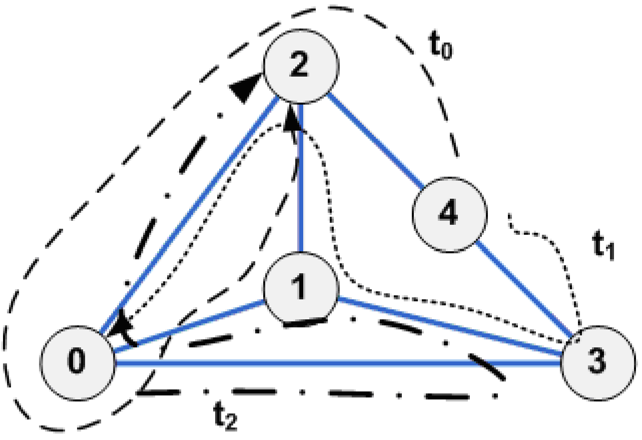
The OnlineDemand includes the source and destination node identifiers. The protection field determines whether the demand is requesting for a 1+1 protected lightpath establishment or an un-protected demand. The last element of the OnlineDemand data structure determines the number of shortest paths (i.e., *k*) that should be computed. This field is only used in the distributed integration scheme.

6.1.6 NPOT Failure Localization

Failure localization and link recovery techniques in transparent (and translucent) optical networks remain among hot research topics. There are two main approaches for failure localization: 1) monitoring cycles (m-cycle) and monitoring trails (m-trail). Both techniques utilize a set of out-of-band lightpaths, which are organized either as optical loops (cycles) or as an open optical circuit (trial). Each link of the network must be covered at least by one m-cycle or one m-trail. Among a large combination for choosing the set of m-cycles/m-trails, the cost of a monitoring solution is given by two parameters: the number of optical channels consumed by the chosen set of cycles/trails, and the number of monitors. The number of monitors is in fact directly provided by the number of cycles/trails in the set since a single monitor is used per cycle/trail. The major objective that must be satisfied by a monitoring solution is that a distinct alarm code could be assigned to each fibre link. This constraint guarantees that any failure can be localized without any ambiguity.

An m-trail is a supervisory optical connection along a single wavelength. An optical signal transmitter is located at the source node of the trail, while the monitor is co-located with the receiver at the destination node of the trail. By definition, an m-trail can traverse a node multiple times but a link at most once. When a link suffers from a failure affecting all the channels crossing it, all the wavelengths, and in particular, those used by the m-trails are disrupted. The monitors placed at the end of the disrupted m-trails will detect the failure and will generate an alarm. By collecting all these alarms, the network operator must be able to localize any single failure.

The failure localization engine, which is integrated in the NPOT is designed and developed based on a novel heuristic algorithm called MeMoTA for "Meta-heuristic for Monitoring Trail Assignment" as explained in detailed in [ADG^{+}09]. This algorithm aims at designing an m-trail solution, which is able to exactly localize the broken link in the network with a low monitoring deployment CAPEX.



(a)

Link	T2	t1	t0	Decimal
(0,1)	1	0	1	5
(0,2)	1	1	1	7
(0,3)	1	0	0	4
(1,2)	0	1	1	3
(1,3)	1	1	0	6
(2,4)	0	0	1	1
(3,4)	0	1	0	2

(b)

Figure 6-2: (a) Example network topology and three m-trails (b) Alarm code table.

The MeMoTA engine determines the optimum placement of monitors in order to make the failure localization and detection possible. Therefore this heuristic algorithm will both function as the NPOT monitor placement and NPOT failure localization module. After constructing the Alarm code table, according to the actual monitor placement, the failure detection will be a simple lookup table operation from the alarm code table. When a failure is occurring in the network, each monitor reports its individual code to the NPOT failure localization module. The failure localization module looks up the alarm code from the alarm code table and localizes the exact failed link. This process is depicted in Figure 6-2 and the following example.

Figure 6-2(a) gives an m-trail solution (t_2, t_1 and t_0) for the network topology that is also depicted in the same figure, and Figure 6-2(b) shows the alarm code table. It can be observed that only 3 m-trails (each with a dedicated monitor) are required to detect (localize) all the link failures. For example if the alarm code is 6, then by looking up the decimal code from the alarm code table, it can be simply identified that the failure is on link (1, 3).

Therefore the MeMoTA algorithm and framework not only provides the failure localization functionality to the NPOT through its alarm table, but also performs the optimum monitor placement during the network planning phase.

6.1.7 NPOT Offline IA-RWA

The NPOT Offline IA-RWA is in fact one of the contributed algorithms from this Ph.D. Thesis. The offline Rahyab is the NPOT Offline IA-RWA engine. This module receives a demand set (or traffic matrix), in the form of (*source, destination, Protection level, and # of LPs*) and computes corresponding lightpath(s) for the given demand set. The *protection level* attribute of a demand determines whether the Offline IA-RWA module should compute a primary and backup (1+1 protection scheme) for the give demand (in case that *Protection Level=1*) or a single lightpath between source and destination node is sufficient (*Protection level =0*). The *# of LPs* determines the required capacity that should be allocated in terms of number of lightpaths between the given source and destination nodes. The detail behaviour and functionality of NPOT_Offline_IARWA (i.e., offline Rahyab) was discussed in Chapter 3.

6.1.8 NPOT Regenerator Placement

The NPOT Regenerator Placement module optimizes the number of regeneration sites and modules that are going to be deployed in the network. This module is developed according to the specification, which is documented in [YAG10]. The code name of the algorithm is COR2P (Cross Optimization for RWA and Regenerator Placement). The Regenerator placement module receives a demand set (traffic matrix) along with the network description and network topology and then optimizes the regeneration sites and ports in the network. The COR2P algorithm invokes the NPOT_QTool in order to evaluate the performance of the optical layer.

6.1.9 NPOT Monitor Placement

In addition to the regenerator placement algorithm, the NPOT exploits a special purpose monitor placement algorithm, which deploys optical impairment/performance monitors (OIM/OPM) in an optimized fashion on the network links. The main goal of monitor placement algorithm is to facilitate the failure localization procedure. The monitor placement algorithm that is integrated in the NPOT is part of the failure localization engine (MoMaTA algorithm), which was presented earlier in Section 6.1.6.

6.1.10 NPOT Messaging Protocol

In order to realize the communication of the NPOT with the other entities in the DICONET control plane integration scheme, a messaging protocol layer is designed and implemented on top of the standard TCP socket interface. Depending on the integration scheme (i.e., distributed or centralized) the actual implementation of this messaging protocol will be different. In particular the IA-RWA algorithm and its functionality are quite different in centralized and distributed integration schemes. Each integration scheme and use-case scenarios are compiled in the rest of this section.

6.2 Control Plane Integration Schemes

In this section two integration schemes in DICONET project will be presented: one based on a **centralized**, PCE architecture, and the other fully **distributed**. Although the two architectures are very different from the control plane point of view, they are very similar from the NPOT perspective, which implements essentially the same functionalities and hence provides the same interface (with minor differences) to each of the two control plane integration schemes. Both architectures are implemented and tested in DICONET project.

6.2.1 Centralized Scheme

The centralized scheme is depicted in Figure 6-3. In the centralized integration scheme Enhanced Path Computation Element (EPCE) will play the role of a centralized engine that computes the lightpaths and respond back to requesters. In addition to the path computation, the EPCE, which includes the DICONET NPOT, is responsible for failure handling. In fact the failure localization module of NPOT receives the alarms from OCCs and after localizing the failure the global TED and global PPD will be updated and the new lightpaths due to the failure will be computed using the NPOT_Online_IARWA module [KCM⁺09]. Then the source node of the affected lightpath(s) will be contacted (NPOT→ OCC) and the new lightpaths will be established using the signalling protocol.

6.2.1.1 Lightpath Establishment Use-Case

In general three lightpath establishment cases can be considered. The soft permanent lightpath establishment, permanent lightpath establishment and finally switched lightpath establishment. In the permanent lightpath establishment, the Network Management System (NMS) directly contact the optical nodes; therefore this case is out of the scope of DICONET test-bed integration. The only difference between soft permanent and switched case is that in the latter case (i.e., switched) the network operator (end user) directly contacts the OCC and there is no need to consider the

NMS interface, except a notification from source node to NMS, which is forwarded by control plane to NMS upon the lightpath establishment. Since the rest of the lightpath establishment will remain the same, the focus will be only on **"Soft Permanent"** connection establishment.

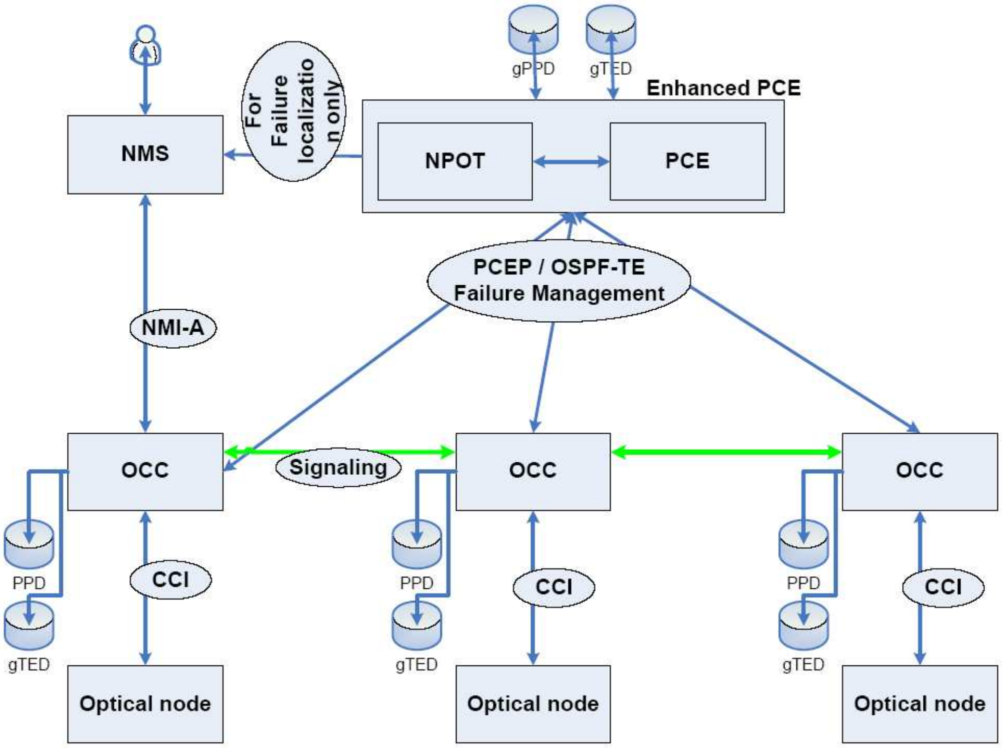


Figure 6-3: Centralized integration scheme.

Before explaining the lightpath establishment procedure, the players in this use case are introduced as follows:

- NMS: Network Management System
- PCE: Path Computation Element
- NPOT: Network Planning and Operation Tool
- NMI-A: Network Management Interface – ASON control plane
- OCC: Optical Connection Controller
- TED: Traffic Engineering Database
- gTED: Global TED
- PPD: Physical Parameter Database
- gPPD: Global PPD
- PCEP: Path Computation Element Protocol
- OSPF-TE: Open Shortest Path First with Traffic Engineering
- OIM: Optical Impairment Monitor
- OPM: Optical Performance Monitor
- CCI: Connection Controller Interface – Interface between OCC and Optical nodes
- EPCE: Enhanced PCE

The lightpath establishment is as follows, with steps concerning NPOT in bold:

1) The user contacts the NMS (GUI) interface, and asks for a lightpath between a pair of source-destination nodes. The demand includes the source and destination nodes to be established and whether the demand is (1+1) protected or restorable (i.e., un-protected).
2) NMS conveys the request to the source node OCC via the NMI-A interface.
3) **The source node OCC contacts the PCE module inside the EPCE (using PCEP protocol) to request a path computation for the given demand. A demand includes the source and destination nodes along with a request for (1+1) protected or un-protected lightpath(s).**
4) **The PCE contacts the NPOT, asking for a lightpath computation (route and wavelength) (will be internally done inside EPCE). The communication protocol for this request is numbered in Star 3.**
5) **NPOT computes the lightpath (using NPOT_Online_IARWA module) and responses back to PCE (will be internally done inside EPCE).**
6) PCE responses back to the requester (source node) using PCEP protocol.
7) The OCC at the source node establish the lightpath using the standard signalling protocols or the OCC will inform the NMS of the un-feasibility of the requested connection (demand). If the lightpath is established the OCC updates the EPCE (in particular NPOT) by sending confirming that the lightpath (with proper lighpathID) is established.
8) **The OCCs update their global gTED databases and also local PPD databases using extended OSPF-TE. The EPCE's gTED and PPD databases are also updated using extended OSPF-TE protocol. In other words, since both PCE and OCCs are all participating in extended OSPF-TE protocol then the global TED and PPD of EPCE and all OCCs are updated accordingly. In the dissemination phase the OCCs update the gTED databases with wavelength availability information using OSPF-TE extended to update TED (but not PPD) and wavelength availability information of links.**
9) OCC node at the source updates the NMS and the EPCE based on the successful or un-successful response from the possible failure of the signalling protocol (in step 7) for lightpath establishment and the NMS GUI will be updated accordingly.

6.2.1.2 Failure Handling Use-Case

The players in the failure use-case remain intact as introduce in Section 5.2.1.1. The failure handling use-case can be explained as follows:

1) The optical node detects the failure and communicate the failure to the OCC. CCI is the interface between optical node and open protocols (e.g SNMP or XML) can be used for communication between OCC and optical node.
2) **OCCs send Alarms to the NPOT module of EPCE. Please note that due to transparency, many OCC nodes will send the alarms to the EPCE and the failure localization component inside NPOT (located inside EPCE) is**

responsible to perform the "Root-cause" analysis to figure out the source of failure.

3) **NPOT utilizes the failure localization component to localize the failure and EPCE updates the gTED and gPPD databases.**
4) **NPOT module of EPCE requests the source OCCs of the lightpaths that should be restored to start the re-routing (i.e., signaling similar to the lightpath establishment) and provides the new routes for the affected lightpaths. Also EPCE updates NMS of the failure location (which will be presented in NMS GUI).**
5) **EPCE floods the failure information using OSPF-TE that will update the gTED and gPPD databases of OCCs in the network.**

6.2.2 Distributed Scheme

The distributed integration scheme is depicted in Figure 6-4. The dynamic lightpath establishment use case will be detailed in the rest of this section. Note that the players of this use-case are the same as with the centralized integration scheme.

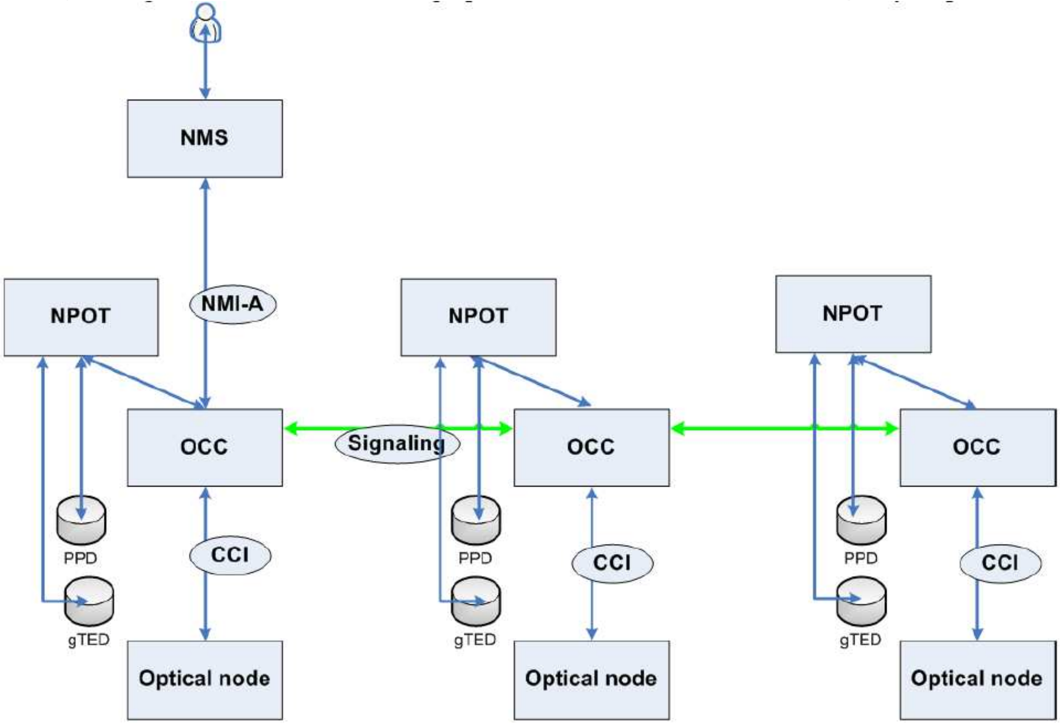


Figure 6-4: Distributed (hybrid) integration scheme.

In the distributed integrated scheme the NPOT module is distributed in the network and is coupled with OCC nodes via NPOT-OCC communication protocol. This protocol is responsible to implement the request-response interaction between OCC and NPOT as will be explained in more details in the use case scenarios. The network description databases (PPD and TED) in this integration scheme are also distributed. During the network boot process, it is assumed that all nodes have a synchronized picture of the network topology and physical characteristics of network elements. However during the operation mode, as will be explained in the use-case scenarios, these databases will be updated properly to reflect the changes in the network.

6.2.2.1 Lightpath Establishment Use-Case

The lightpath establishment use-case for the distributed integration schemes will take place as follows:

1) The end-user requests a lightpath establishment from source to destination (via User-NMS interaction interface)
2) The NMS contacts the OCC at the source node using NMI-A interface.
3) OCC at the source node contacts the NPOT_Online_IARWA module and request for a route (or a pair of routes in case of protected demand). In the distributed (hybrid) case, the NPOT provides the route since the wavelength for the lightpath is “assigned” during the signalling phase.
4) **NPOT_Online_IARWA computes the lightpath and responds back to OCC.**
5) **If a route is found the OCC at the source node starts the extended signalling protocol to establish the lightpath from source to destination and the local PPD database will be updated using extended RSVP-TE.**
6) **The QoT value is computed in the destination node using the Pot’s Q-Tool module and also for all the established lightpaths that share the same links with this lightpath to make sure that the active lightpaths are not disrupted due to excessive cross-talk introduced by the current lightpath.**
7) **In the dissemination phase the OCCs update the gTED databases with wavelength availability information using OSPF-TE extended to update TED (but not PPD) and wavelength availability information of links. OCC utilizes the messaging protocol 1 (indicated as Star 1) to update the TED database of NPOT.**
8) Based on the outcome of the lightpath establishment (the source node) updates the NMS GUI.

The steps in which the NPOT is involved appear in bold letters.

6.3 Performance Evaluation of NPOT

In this section the performance of the DICONET NPOT with respect to the impairment aware network planning is presented. The experimental evaluation of DICONET NPOT for Centralized and Distributed control plane integration schemes is reported in [AAA$^+$10].

In the planning mode the performance of the Offline Rahyab (as defined in Chapter 3) is compared with a tool named DIAMOND. DIAMOND is a planning tool that searches for a lightpath between two nodes in a network by means of a layered network graph. The path search is iterative and places a regenerator or wavelength converter whenever it is required (due to QoT or wavelength continuity constraints, respectively). The chosen path is the one having the lower cost, which is obtained considering the link lengths and the eventual cost associated to intermediary opto-electronic devices. The path search is a heuristic based on the A* algorithm [MBL$^+$08]. The traffic demands are considered in the arrival order and they are routed sequentially. A demand is blocked whenever there is no available resource, in terms or of wavelengths in the fibre either of opto-electronic devices in an intermediate node. The Q-factor is estimated by a polynomial function (QoT-estimator) considering the accumulation of the main effects degrading the signal propagation, such as ASE, CD and PMD, FC and nonlinearities (Please refer to Chapter 2 for the definition of these impairments). To consider estimation uncertainties associated to an estimate, a fixed margin is added to the estimated Q-factor. DIAMOND utilizes A* heuristic, considering the resource availability and not accounting for QoT degradation due to neighbouring lightpaths. First-fit wavelength assignment on available path with lower cost is utilized in this IA-RWA engine. In order to guarantee the feasibility of a candidate lightpath, the QoT-estimator considers the worst case scenario for all connection, i.e., all neighbour channels are present.

Offline Rahyab (as defined in Chapter 3) finds the optimum lightpath considering the degradation due to neighbouring lightpaths. Offline Rahyab intensively uses the Q-Tool (version 3.33) to evaluate the QoT of the already established lightpaths in order to admit or reject a new demand. This means that Q-Tool is less pessimistic than the DIAMOND QoT estimator and can enable saving of regenerators. The main advantage of DIAMOND is its computation speed, while NPOT (and offline Rahyab) requires more time to compute the optimum solution.

6.3.1 Simulation Setup

A Deutsche Telekom's national network-based topology (DTNet) is selected for our simulation studies (see Appendix A). This network has an average node degree of 3.29 and average link length of 186 km. The physical characteristics of the network, which are considered as inputs to the Q-Tool are summarized in Table 6-1. The offered load in the network as the ratio between the number of lightpath demands divided by the number of pairs of nodes in the network. The unit traffic load corresponds to the demand set where there is a lightpath request between each pair of (distinct) source-destination pair. Three traffic load values (i.e., 0.3, 0.6 and 0.8) were studied, corresponding here to the establishment of 56, 110 and 146 lightpaths.

Table 6-1: Physical characteristics of DTNet

Parameter	Value
Input power	-4 (SSMF), 3 (DCF) dBm
Pre-dispersion compensation	-85 ps/nm
Span length	70 km
Dispersion parameter	17 (SSMF), 80 (DCF) ps/nm/km
Attenuation	0.23 (SSMF), 0.4 (DCF) dB/km
PMD	0.1 ps/(km)$^{1/2}$
Channel spacing	50 GHz
Amplifier noise figure	6 dB
Mean under compensated dispersion	80 ps/nm per span
Q-factor threshold	15.5 dB (BER=10^{-9} without FEC)
Line rate	10 Gbps
Number of channels per fiber	16

In Figure 6-5 the Q-factor value (computed by Q-Tool) of 10 shortest paths between all possible pairs of the nodes is depicted. Without considering the impact of other established lightpaths, there is no lightpath with a length longer than 1500 km and acceptable QoT. There are short lightpaths with Q value lower than threshold

(Region 1) and long lightpaths with acceptable Q values (Region 2). This demonstrates the benefit of IA-RWA engines, which are able to find long but feasible lightpaths. Routing engines, such as A*, which only consider the shortest paths or worst case scenario are not able to properly explore the solution space.

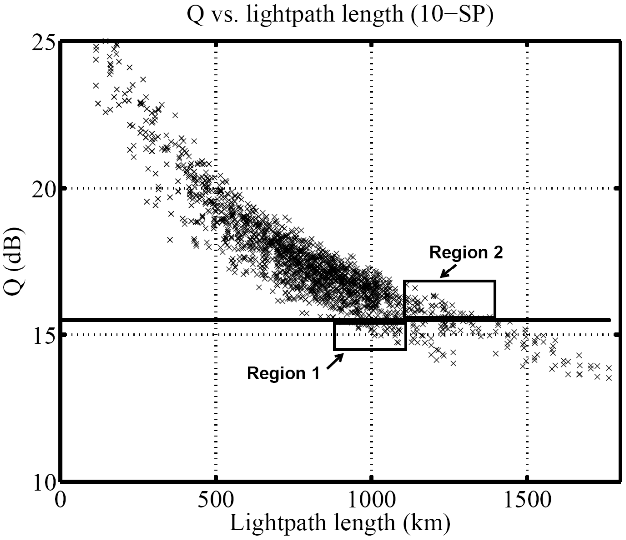


Figure 6-5: Benefit of IA-RWA and different solution spaces.

6.3.2 Results

NPOT and DIAMOND served all demands without any blocking for all loads. NPOT served all demands without any regenerators and there was no need to transform the demand set. However DIAMOND computed a need for 2 and 6 regenerators for load values 0.6 and 0.8 respectively. This is mainly due to wavelength contention. Indeed DIAMOND utilizes the first-fit wavelength assignment and due to sequential path search, wavelength blocking can occur, which is alleviated by wavelength conversion using opto-electronic regeneration.

The offline Rahyab module of NPOT intensively invokes the Q-Tool to evaluate the performance of each candidate lightpath in order to guarantee the minimum QoT impact of the new lightpath on the currently established ones. Therefore the computation time of NPOT is very high compared to DIAMOND. The computation time of NPOT for load 0.3 was 9 hours while DIAMOND computes the results in 563 ms. The computation time in planning phase is not critical. Besides the acceleration of QoT estimation process (i.e., FPGA Accelerated Q-Tool) will resolve this issue.

The cumulative distribution function of the lightpath length for different loads is depicted in Figure 6-6. The distribution of the lightpaths length is presented in Figure 6-7 for all 3 demand sets combined. It can be observed that diverse routing engine of NPOT could find longer feasible lightpaths compared to DIAMOND. The average length of the lightpaths in DIAMOND is 419 km and 572 km for NPOT. Almost all computed lightpaths by DIAMOND have a length lower than 900 km. NPOT only considers the active lightpaths in order to admit or reject a demand, while DIAMOND considers a worst cast scenario, in which all neighbouring lightpaths are active. As argued in Figure 6-5 NPOT can find longer feasible lightpaths compared to DIAMOND.

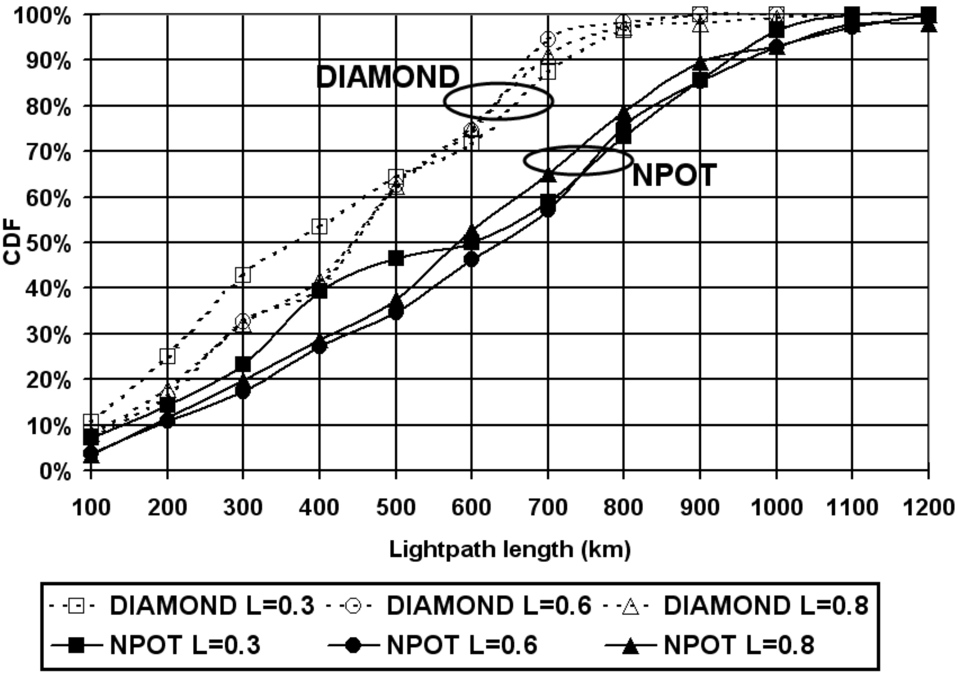


Figure 6-6: CDF of lightpath length for different values of loads.

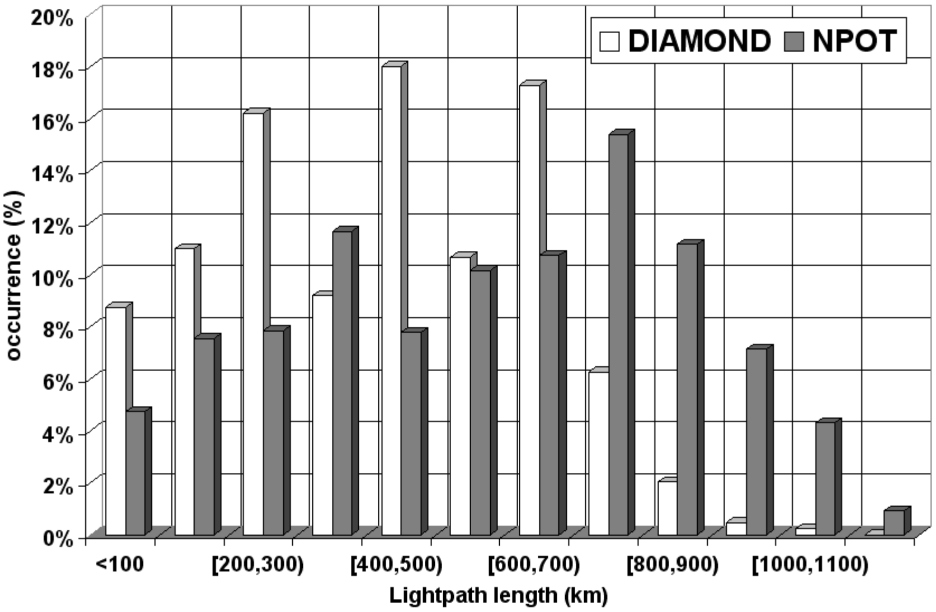


Figure 6-7: Distribution of lightpaths length.

Figure 6-8 presents the distribution of wavelength usage by DIAMOND and NPOT for a particular demand set (i.e., Load=0.3). Rahyab utilizes an adaptive wavelength assignment approach, in which the wavelength of the candidate lightpath is selected in a way that it introduces the minimum impact on the currently established lightpaths. The A* engine of DIAMOND follows the first fit wavelength assignment on available path with fewer regeneration cost. The offline Rahyab wavelength usage pattern is adaptive along the available channels per links depending on network state and some channels are not assigned to any lightpath. It was observed that for the given demand sets on average the first 10 channels on the links were sufficient for both planning tools to serve 80% of the demands.

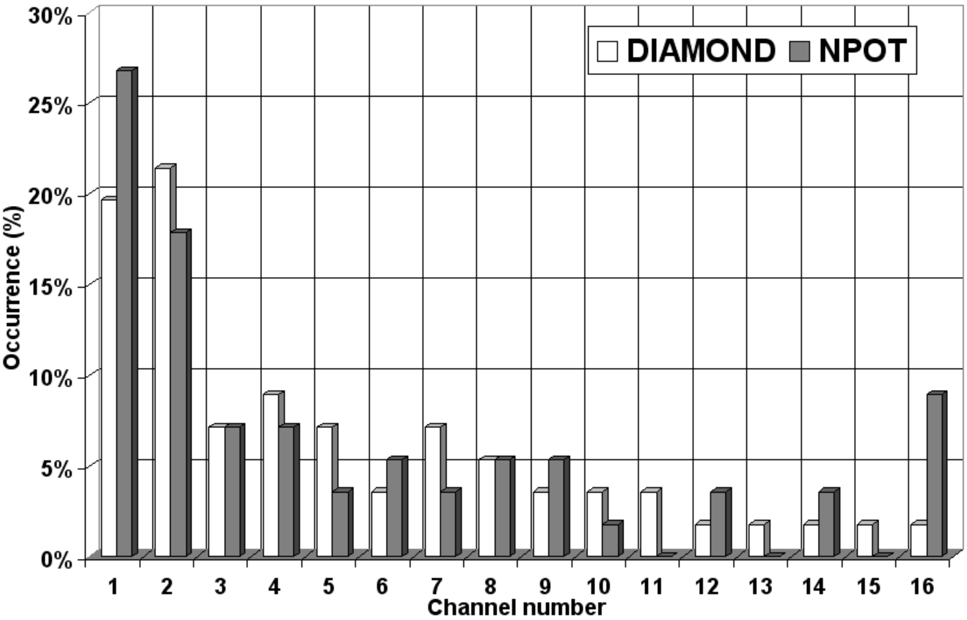


Figure 6-8: Frequency of channel usage (Load=0.3).

NPOT and DIAMOND rely on different QoT estimators. In order to evaluate the quality of the solutions of these tools, the IA-RWA solution of each tool for each demand set is fed to the NPOT's Q-Tool (Q-Tool ver. 3.33). The average Q value of DIAMOND's solutions is 4% better than NPOT (Figure 6-9). The average Q-factor of DIAMOND's solution (over three demand sets) is 28 dB. This is mainly due to the fact that DIAMOND routing module selects shortest paths in general to admit or reject a demand.

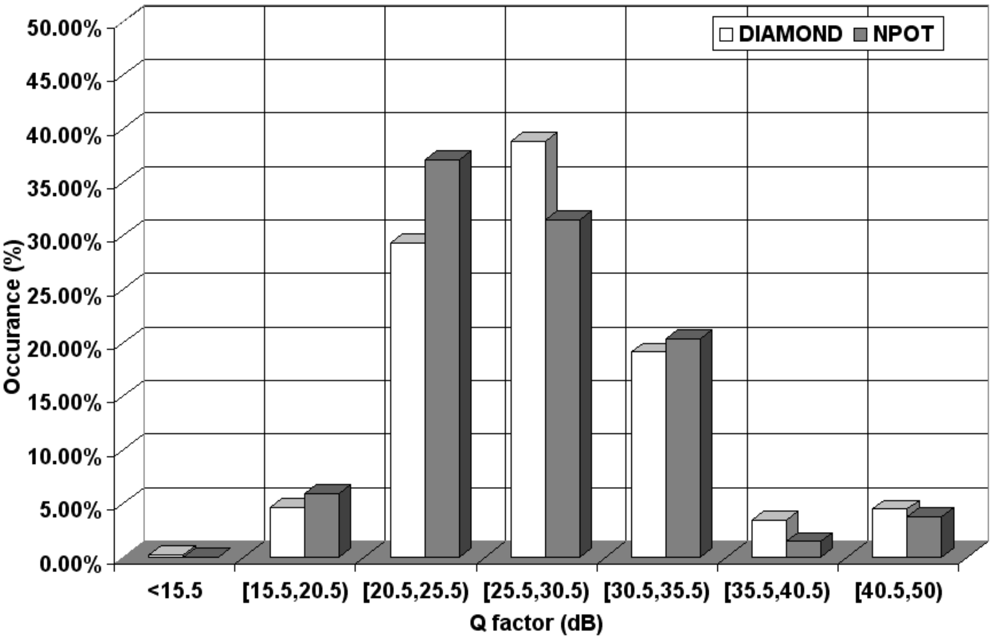


Figure 6-9: Distribution of Q values for IA-RWA solutions of DIAMOND and NPOT.

6.4 Chapter Summary

In this chapter the design and development of DICONET NPOT was presented. The key innovation of DICONET is the development of a network planning and operation tool (NPOT) residing in the core network nodes that incorporates real-time assessments of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. The modular design of NPOT paved the way to include offline Rahyab as the IA-RWA planning module of NPOT.

In the planning mode, the NPOT includes three building blocks, with direct interface to the network management system and/or network designer/architect. These three modules are: 1) Offline IA-RWA (offline Rahyab as presented in Chapter 3), 2) Regenerator placement module, and 3) Optical Monitor Placement module. The offline IA-RWA, receives a demand set (traffic matrix) and finds the proper lightpaths (routes and available wavelengths) for each demand. The regenerator placement module computes the optimum locations (and number of regeneration ports) for the cases that the QoT of the certain lightpaths cannot be met in all-optical (full transparency) mode.

In order to properly address the failure localization in transparent network, the optical monitor placement module, determines the network links that should be equipped with optical impairment/performance monitors. These monitors provide the required information for failure localization algorithm, which is utilized in NPOT operation mode.

The description of the network (both physical layer specification and the network topology are fed to the NPOT in the form of physical parameter database and traffic engineering database (i.e., PPD and TED). In the planning the computation for lightpaths considers the impact of physical layer impairments and computes the lightpaths in a way that the required quality of transmission (QoT) is guaranteed to be above a required threshold.

The operation mode of NPOT can be further divided to the 1) centralized and 2) distributed (hybrid) control plane integration scheme. In the centralized scheme the NPOT is interfaced to a path computation element (PCE), which plays the role of a centralized entity for path computation. In this integration scheme the functionality of the PCE is extended by the features and functionalities of the NPOT. The actual path computation is performed by NPOT Online IA-RWA engine and besides the failure localization module of the NPOT detects the location of the failures. In the distributed integration scheme the extended signalling protocol (i.e., RSVP-TE) and NPOT's diverse routing engine (online IA-RWA) are functional units for the operation of the NPOT in this mode. In addition to these components, there are other building blocks like network description repositories, interfacing protocols (i.e., TCP based messaging protocols) and repository generators and the physical layer performance evaluator (i.e., Q-Tool).

In this chapter the result of performance evaluation of NOPT and a similar tool (i.e., DIAMOND) was presented. NPOT managed to find longer feasible lightpaths compared with DIAMOND. The offline Rahyab wavelength assignment engine usage pattern is adaptive along the available channels per links depending on network state and some channels are not assigned to any lightpath. It was also observed that for the given demand sets on average the first 10 channels on the links were sufficient for both planning tools to serve 80% of the demands. The average Q value of DIAMOND's solutions is 4% better than NPOT. The average Q-factor of DIAMOND's solution (over three demand sets) is 28 dB. This is mainly due to the fact that DIAMOND routing module selects shortest paths in general to admit or reject a demand.

Chapter 7:

7. Conclusions and Future Works

Routing and Wavelength Assignment is the core component in planning and operation of optical networks. Considering the physical layer impairments in the RWA decisions adds a new dimension to this problem. Heuristics, meta-heuristics and optimization techniques are proposed as algorithmic approaches to solve IA-RWA problems. The general approach to address the IA-RWA problem can be divided in two main categories. The first trend utilizes traditional RWA algorithms and after selecting the lightpath the physical constraints are verified. The second approach is to use some metrics, which are related to the PLI constraints as cost of the links in order to compute the shortest path(s). The physical impairments and IA-RWA algorithms can be incorporated in control planes using various integration approaches.

There are quite few proposals that address the resilience and protection issues in the IA-RWA algorithms. In addition to simulation studies, experimental and some analytical models are available to evaluate the performance of the proposed algorithms. None of the surveyed works considers the inaccuracy of the physical impairment information (analytically computed or measured) into their IA-RWA algorithms. The proposed adaptive IA-RWA algorithms simply change their decisions assuming that the physical information are completely accurate.

As light propagates through a lightpath in the transparent optical networks, physical layer impairments accumulate on the transmitted signal. Therefore, it is possible to provision a lightpath, while its quality of transmission (QoT) does not meet the required threshold. One of the key building blocks in an impairment aware planning and operation methodology for optical networks planning and design is a QoT estimator, which is typically a combination of theoretical models and/or interpolations of measurements, usually performed offline, but also possibly online. A practical QoT estimator should be fast to ensure that lightpaths can be established in real time of course with proper accuracy. Physical layer impairments can be classified into linear (i.e., attenuation, CD, PMD, FX, crosstalk, ASE noise, insertion loss, and PDL) and nonlinear (i.e., SPM, XPM, FWM, SBS, SRS) effects. Analytical models (e.g., Q-Factor) or a hybrid approach considering analytical, simulation and experiments are proposed for modelling the physical impairments and incorporating their impacts in RWA algorithms. In addition to the detailed description of physical layer impairments, findings regarding the physical layer impairments models that are reported in the state-of-the-art literature were also presented.

Our novel algorithm for impairment aware network planning (Offline Rahyab) along with its performance compared with impairment unaware and two impairment aware algorithms from literature were presneted. As mentioned in the introduction, the RWA problem is usually considered fewer than two alternative traffic models.

When the set of connection requests is known in advance, the problem is referred to as network planning (or *offline* or *static* RWA), while when the connections arrive randomly and are served on a one-by-one basis the problem is referred to as network operation (*online* or *dynamic* RWA). The offline Rahyab algorithm solves the offline traffic problem in a sequential manner. Initially, it orders the connection requests according to some appropriate criterion and then serves the connections on a one-by-one basis. The demands are served in a way that the impact of establishing each demand (lightpath establishment) on the currently established lightpaths will be minimized.

Offline Rahyab demonstrated good wavelength utilization and blocking performance when the number of wavelengths is limited; however, as the traffic load increases its ability to find zero blocking solution is not that good, due to the fact that it does not optimize the lightpaths for all connections jointly, but on a one-by-one basis. An advantage of this heuristic is that it can provide different protection levels to the connection requests.

The offline RWA problem is particularly interesting from a network designing perspective, since a good designed RWA algorithm can optimize the resources (e.g., minimize the number of wavelengths used to establish the requested connections), and also leave room for serving future connections. The incorporation of physical impairments in an offline routing algorithms permits cross-layer optimization, improving the signal quality of the lightpaths (avoid lightpath interference), leading to lower physical-layer blocking probability, and also allowing future connections to be established with higher probability because the already established lightpaths have an optimal or near optimal signal quality.

Offline algorithms are usually time-consuming, since the RWA problem (even without physical impairments or even if routing and wavelength assignment processes are considered separately) has been shown to be NP-Complete. Although it is not necessary for offline algorithms to have low running times, as it is for online algorithms, large scale experiments can be intractable. Finally, the performance of *offline Rahyab* were demonstrated, as an engine for re-routing the demands due to the failure in the network.

Online IA-RWA algorithm (i.e., Online Rahyab) were also presneted. This algorithm utilizes a multi-constraint framework. Online Rahyab utilizes an MCP framework based on a single mixed metric for computing a couple of candidate paths between source and destination nodes, for a dynamic demand. This strategy could be based on the well-known Dijkstra shortest path algorithm. Furthermore, this MCP engine for diverse routing (e.g., the Bhandari algorithm) for protection purposes (e.g., 1+1) or generic k-shortest path algorithms can be exploited.

The performance of four different online IA-RWA algorithms were compared: Sigma-Bound, Multi-Parametric, online Rahyab and 3-SP-Q, under common scenarios, QoT estimator and network topology. For the Sigma-Bound algorithm the Most Used Wavelength (MUW) with re-routing and the Mixed optimization functions (Mxed) were used, while for the Multi-Parametric the minTP optimization function was utilized. The online Rahyab algorithm has a good blocking rate performance; however its execution time is very large. The main reason for this behaviour is that the Rahyab algorithm uses the Q-Tool at its intermediate steps to select among the set of ‘useable’ (candidate) lightpaths, the one that introduces the minimum impact on the currently established lightpaths. The performance of online Rahyab algorithm can be considerably improved by accelerating the performance of the Q-Tool (e.g., using FPGA hardware acceleration).

A variation of online IA-RWA algorithm was presented that considers the availability of the OIM/OPM monitors in the network within the routing and wavelength assignment process. Indeed, a fundamental aspect for an IA-RWA strategy in order to be actually implemented is to utilize Optical Impairment/Performance Monitoring (OIM/OPM) for evaluation of signal quality. In addition to the exploitation of monitoring information in IARWA engines, it is also useful to incorporate the availability of OIM/OPM monitors in QoT estimations (e.g., Q-Tool). It was shown that for a system with 10 channels per fibre, 40% more lightpaths can be accommodated if high confidence in the Q estimations is available compared with the case where high accuracy is not available. The performance of proposed algorithm were compared with two other algorithms that were selected from state-of-the-art IA-RWA algorithms. The simulation results indicates that utilizing the optical monitors in the network can improve the performance of the IA-RWA algorithms by roughly more than 50% for high traffic load or limited number of channels. The admissible load for a given blocking rate is 11% higher than the one which is allocated by an algorithm that does not consider the OIM/OPM deployment in the network. It was demonstrated that due to the important impact of QoT estimator inaccuracies on network dimensioning (here, in terms of blocking rate), RWA algorithms need to incorporate those inaccuracies in order to appropriately reflect the actual behaviour of monitored transparent optical networks.

Finally, the design and development of DICONET NPOT was presented. The key innovation of DICONET is the development of a network planning and operation tool (NPOT) residing in the core network nodes that incorporates real-time assessments of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. The modular design of NPOT paved the way to include offline Rahyab as the IA-RWA planning module of NPOT.

In the planning mode, the NPOT includes three building blocks, with direct interface to the network management system and/or network designer/architect. These three modules are: 1) Offline IA-RWA (offline Rahyab as presented in Chapter 4), 2) Regenerator placement module, and 3) Optical Monitor Placement module. The offline IA-RWA, receives a demand set (traffic matrix) and finds the proper lightpaths (routes and available wavelengths) for each demand. The regenerator placement module computes the optimum locations (and number of regeneration ports) for the cases that the QoT of the certain lightpaths cannot be met in all-optical (full transparency) mode.

In order to properly address the failure localization in transparent network, the optical monitor placement module, determines the network links that should be equipped with optical impairment/performance monitors. These monitors provide the required information for failure localization algorithm, which is utilized in NPOT operation mode.

The operation mode of NPOT can be further divided to the 1) centralized and 2) distributed (hybrid) control plane integration scheme. In the centralized scheme the NPOT is interfaced to a path computation element (PCE), which plays the role of a centralized entity for path computation. In this integration scheme the functionality of the PCE is extended by the features and functionalities of the NPOT. The actual path computation is performed by NPOT Online IA-RWA engine and besides the failure localization module of the NPOT detects the location of the failures. In the distributed integration scheme the extended signalling protocol (i.e., RSVP-TE) and NPOT's diverse routing engine (online IA-RWA) are functional units for the operation of the NPOT in this mode. In addition to these components, there are other building blocks like network description repositories, interfacing protocols (i.e., TCP based messaging protocols) and repository generators and the physical layer performance evaluator (i.e., Q-Tool).

The result of performance evaluation of NOPT and a similar tool (i.e., DIAMOND) were also presneted.NPOT managed to find longer feasible lightpaths compared with DIAMOND. The offline Rahyab wavelength assignment engine usage pattern is adaptive along the available channels per links depending on network state and some channels are not assigned to any lightpath. For the given demand sets on average the first 10 channels on the links were sufficient for both planning tools to serve 80% of the demands. The average Q value of DIAMOND's solutions is 4% better than NPOT. The average Q-factor of DIAMOND's solution (over three demand sets) is 28 dB. This is mainly due to the fact that DIAMOND routing module selects shortest paths in general to admit or reject a demand.

The following issues are identified that could be addressed in future works:

- As indicated in Chapter 2, there are few works in the state-of-the-art surveyed papers that consider the advanced modulation formats and Raman amplifiers in their studies. Also higher bit rates and the challenges that they will introduce are areas that require more research. The combination of different data rates and modulation formats introduce new challenges towards planning and operation of optical networks. Considering the impact of novel modulation formats on planning and operation decisions is an interesting topic for further investigation.
- The contributed algorithm for planning mode does not consider the regeneration and regenerator usage. One of the future works could be the consideration of 3R regenerations for translucent or optical-bypass networks.
- The contributed MCP framework can be utilized in order to include energy consumption of the links and components on the links and nodes in order to add energy awareness to the IA-RWA algorithm.

Appendix A

Appendix A: Network Topologies

A.1 DTNet

Many of the performance evaluation studies and similar studies are performed using the Deutsche Telekom's National Network (DTNet) as depicted in Figure A.1. This network has 14 nodes and 23 bidirectional links, with an average node degree of 3.29.

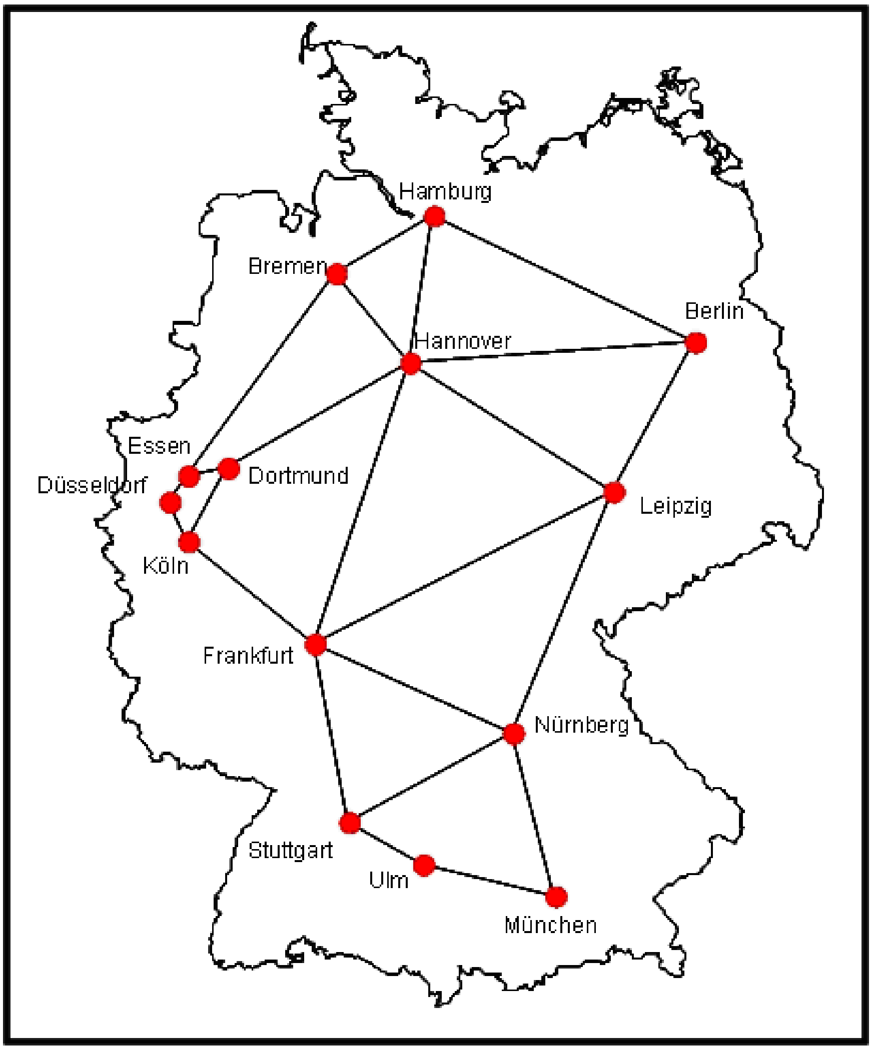


Figure A.1: Topology of DTNet.

Node IDs, Node names and short name for nodes are presented in Table A.1.

Table A.1: Node ID and Node name of DTNet

Node ID	Name	Short Name
1	Berlin	B
2	Bremen	HB
3	Dortmund	Do
4	Düsseldorf	D
5	Essen	E
6	Frankfurt/Main	F
7	Hamburg	HH
8	Hannover	H
9	Köln	K
10	Leipzig	L
11	München	M
12	Nüurenburg	N
13	Stuttgart	S
14	Ulm	U

The demand set (Traffic matrix) of DTNet is presented in Table A.2.

Table A.2: Demand set of DTNet

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	8.98	12.35	13.64	9.74	32.70	19.34	21.04	14.59	33.68	15.40	12.32	23.74	11.07
2	8.98	0.00	5.76	6.23	4.51	14.19	9.92	10.56	6.59	12.59	6.43	5.13	10.15	4.69
3	12.35	5.76	0.00	12.27	10.90	21.94	11.38	13.34	12.17	17.73	9.33	7.50	15.10	6.88
4	13.64	6.23	12.27	0.00	12.52	24.58	12.48	14.31	18.02	19.54	10.42	8.33	16.96	7.68
5	9.74	4.51	10.90	12.52	0.00	17.29	8.95	10.25	10.46	13.96	7.39	5.92	11.98	5.45
6	32.70	14.19	21.94	24.58	17.29	0.00	28.99	33.09	27.13	47.75	26.20	21.64	27.56	19.88
7	19.34	9.92	11.38	12.48	8.95	28.99	0.00	20.87	13.26	26.42	13.30	10.60	20.84	9.65
8	21.04	10.56	13.34	14.31	10.25	33.09	20.87	0.00	15.16	30.04	14.81	11.94	23.42	10.79
9	14.59	6.59	12.17	18.02	10.46	27.13	13.26	15.16	0.00	20.96	11.22	8.99	18.44	8.30
10	33.68	12.59	17.73	19.54	13.96	47.75	26.42	30.04	20.96	0.00	22.38	18.38	34.50	16.09
11	15.40	6.43	9.33	10.42	7.39	26.20	13.30	14.81	11.22	22.38	0.00	10.82	20.38	10.49
12	12.32	5.13	7.50	8.33	5.92	21.64	10.60	11.94	8.99	18.38	10.82	0.00	16.32	7.82
13	23.74	10.15	15.10	16.96	11.98	27.56	20.84	23.42	18.44	34.50	20.38	16.32	0.00	17.52
14	11.07	4.69	6.88	7.68	5.45	19.88	9.65	10.79	8.30	16.09	10.49	7.82	17.52	0.00

Other characteristics of this network are also summarized in Table A.3. Please note that in Table A.3 all-pair shortest path (e.g., all-pair Dijkstra) is computed for deriving the path statistics and the metric for shortest is the total length of the path (expressed in km).

Table A.3: DTNet characteristics

Parameter	Value
Number of Nodes:	14
Number of links:	23
Node degree:	3.29 (min. 2, Max. 6)
Link length (km):	186 km (min. 37, Max:353 km)
Span length (km):	25 km (Long Aggr.), (min.:0.21, Max:65) 97 km (Short Aggr.), (min: 37, Max.:149)
Number of Spans:	7.5 (Long Aggr.), (min: 1, Max:17) 1.87 (Short Aggr.), (min: 1, Max: 3)
Path length (km):	410 km (min.:37, Max.:874)
Hop count:	2.35 (min:1, Max:5)

The demand matrix for 2009 is forecasted (projected) and calculated based on the population density, considering the population growth. The overall traffic demand is summed to 2.8 Tbit/s. This demand matrix was shown in Table A.2. In this table the ID are the corresponding assigned number to each node name and can simply mapped to the actual node names using Table A.1.

In Figure A.2, the distributions of the link length are depicted. This distribution is shown both in terms of frequency of the link lengths (km) in the network topology and also in term of percentage. More than 20% of the links (5 links) are in the range of 150 to 200 km in this network. Only three links are less than 50 Km long in length and furthermore there is no link with a length more than 400 km.

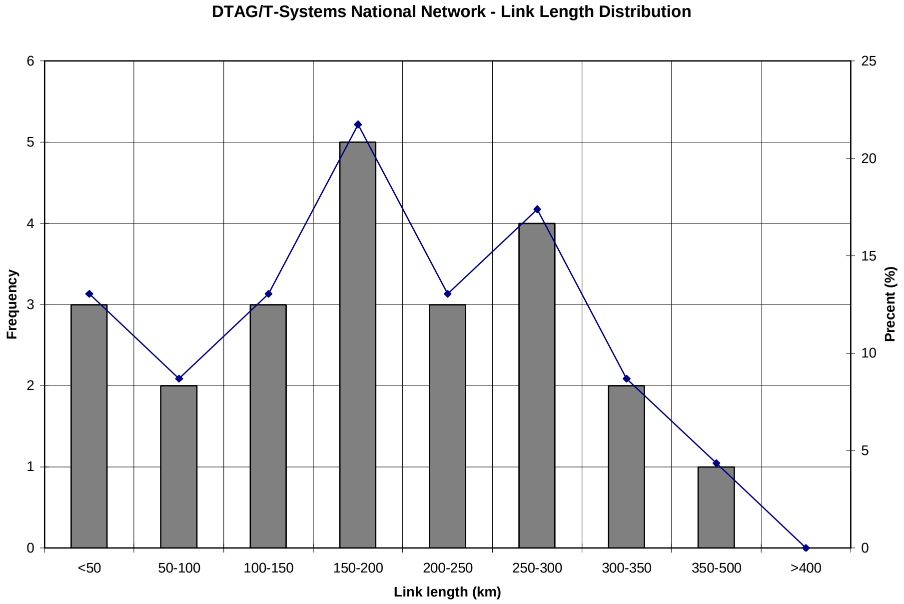


Figure A.2: Distribution of link length in DTNet.

In Figure A.3 the cumulative distribution of the link length are shown. According to this graph more than 80% of the links, have lengths less than 300 km in this network. The next graph (Figure A.4) presents some statistics for the path length in this network. In order to compute this statistics, an all-pair shortest path algorithm was utilized. The distribution is reported both in the form of frequency, percentage and also in the form of CDF. These characteristics are depicted in Figure A.2 and Figure A.3 respectively.

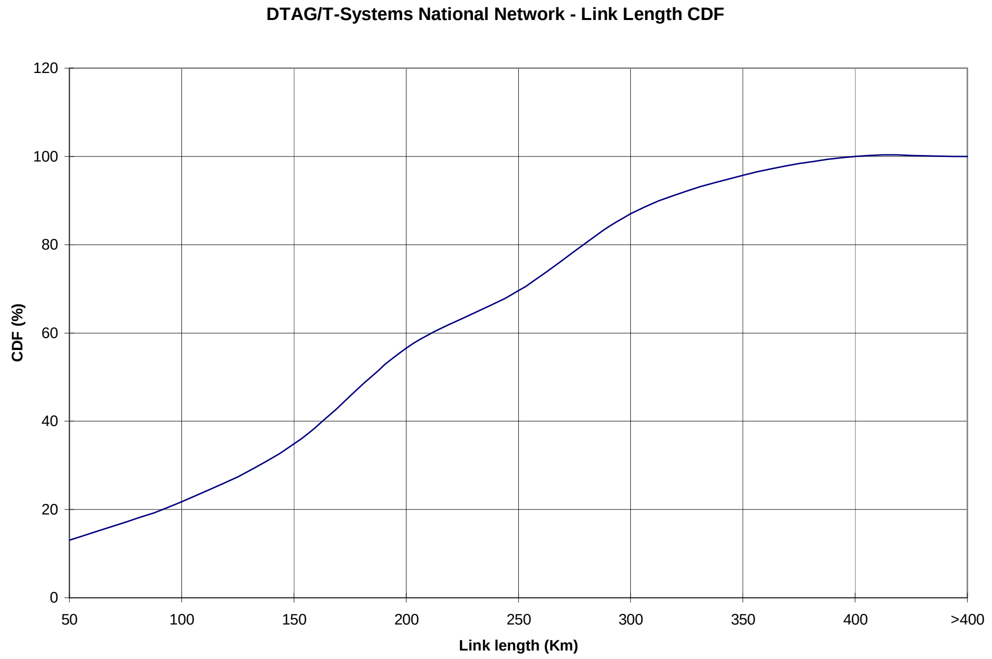


Figure A.3: Link length CDF.

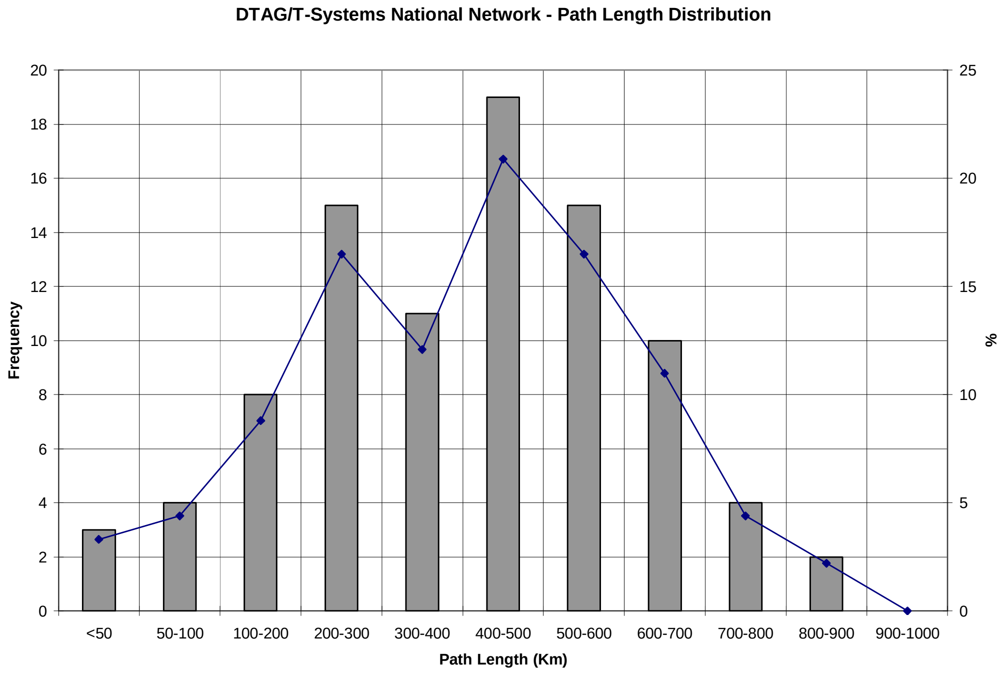


Figure A.4: Shortest path length distribution in DTNet.

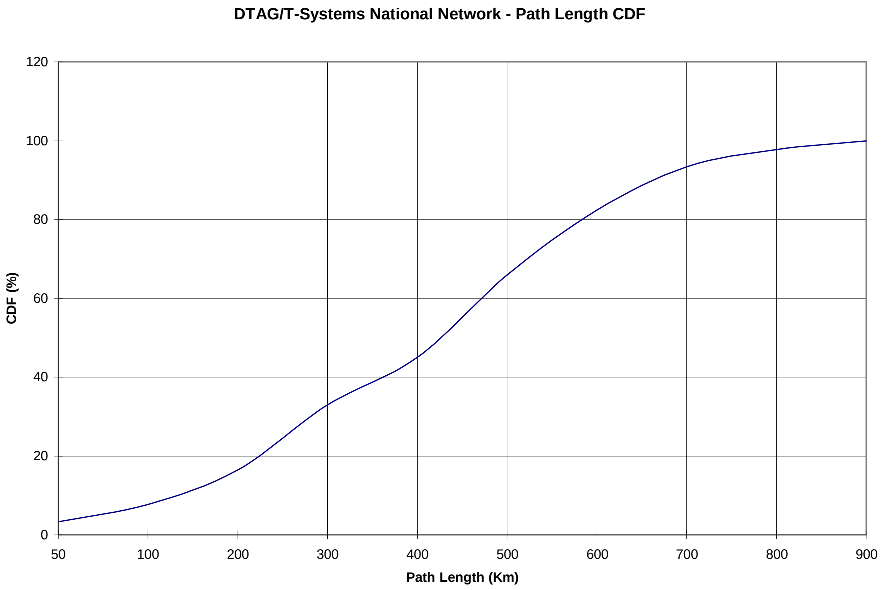


Figure A.5: Shortest path length CDF.

From these two graphs useful information can be extracted about the actual distances between all pairs in the network and out of 91 possible path, more than 60% of them (i.e., approximately 55 path) are less than 500 km in length. Furthermore all possible shortest paths are less than 900km in this network topology.

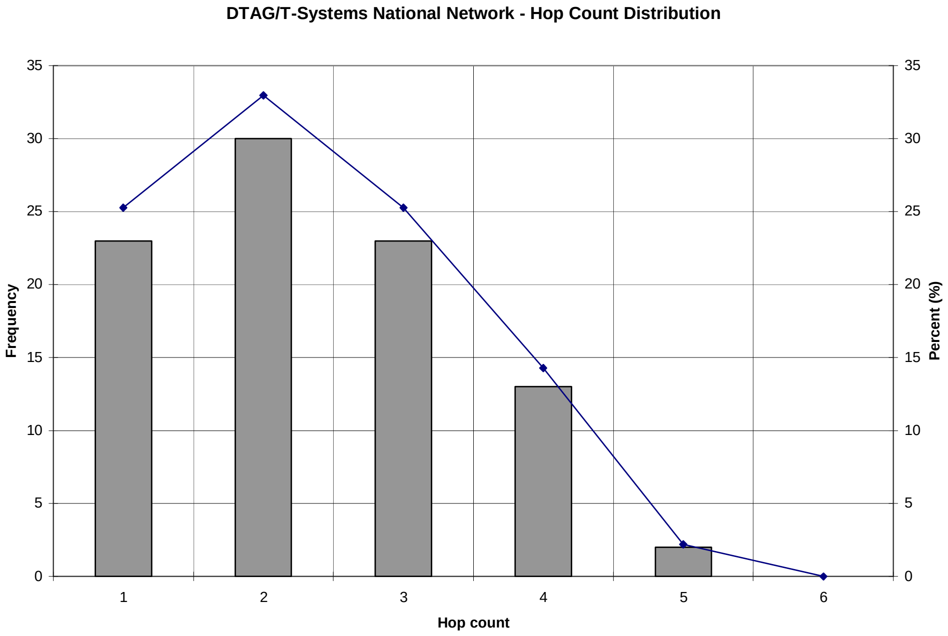


Figure A.6: Distribution of hop counts (for shortest paths) in DTNet.

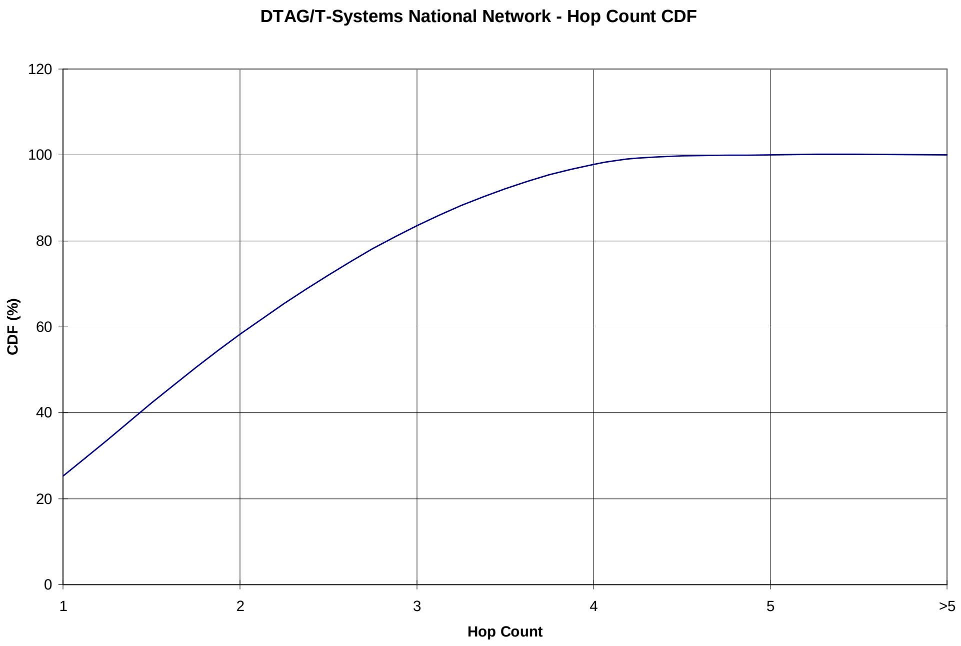


Figure A.7: CDF of Hop counts in DTNet.

A.2 European Optical Network Topology

The European Optical Network (EON) topology is depicted in Figure A.8.

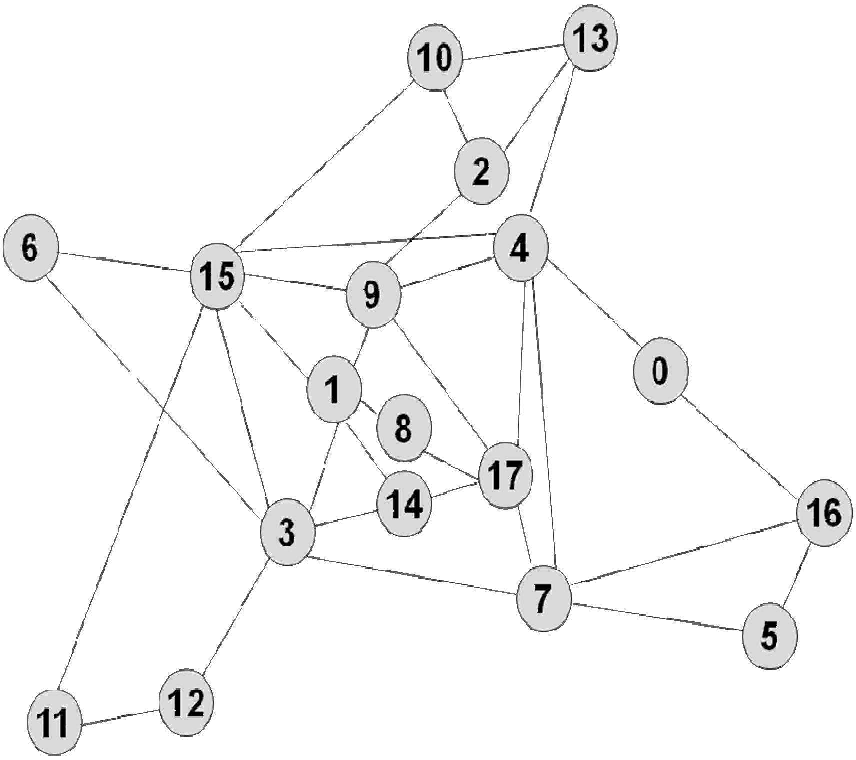


Figure A.8: EON network topology.

Demand set (Traffic matrix) expressed in Gbps (upper triangle) and the link lengths in Km (lower triangle) of EON network are summarized in Table A.4.

Table A.4: Demand set and link lengths of EON network.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	■	8.5	8.5	17.0	76.5	8.5	8.5	42.5	8.5	8.5	8.5	8.5	8.5	8.5	25.5	17.0	8.5	8.5
1	-	■	8.5	51.0	68.0	8.5	8.5	17.0	8.5	34.0	8.5	8.5	8.5	8.5	25.5	34.0	8.5	8.5
2	-	-	■	8.5	25.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
3	-	261.2	-	■	93.5	8.5	8.5	42.5	8.5	42.5	8.5	8.5	34.0	17.0	51.0	85.0	8.5	8.5
4	523.6	-	-	-	■	17.0	8.5	76.5	17.0	68.0	17.0	8.5	34.0	51.0	93.5	68.0	17.0	17.0
5	-	-	-	-	-	■	8.5	17.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
6	-	-	-	857	-	-	■	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
7	-	-	-	1102	735.1	1052	-	■	8.5	17.0	8.5	8.5	25.5	8.5	51.0	25.5	8.5	8.5
8	-	115.8	-	-	-	-	-	-	■	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
9	-	205	730	-	680	-	-	-	-	■	8.5	8.5	17.0	8.5	25.5	42.5	8.5	8.5
10	-	-	550	-	-	-	-	-	-	-	■	8.5	8.5	8.5	8.5	8.5	8.5	8.5
11	-	-	-	-	-	-	-	-	-	-	-	■	17.0	8.5	8.5	8.5	8.5	8.5
12	-	-	-	1100	-	-	-	-	-	-	-	583	■	8.5	17.0	8.5	8.5	0.0
13	-	-	561	-	811	-	-	-	-	-	418.8	-	-	■	8.5	8.5	8.5	8.5
14	-	488.7	-	302.9	-	-	-	-	-	-	-	-	-	-	■	25.5	8.5	8.5
15	-	380	-	484	934.3	-	570	-	-	401	1154	1597	-	-	-	■	8.5	8.5
16	320	-	-	-	-	1073	-	590	-	-	-	-	-	-	-	-	■	8.5
17	-	-	-	-	379	-	-	1200	371.2	714.5	-	-	-	-	530.4	-	-	■

A.3 Internet 2 Network Topology

The Internet-2 network topology is depicted in Figure A.9.

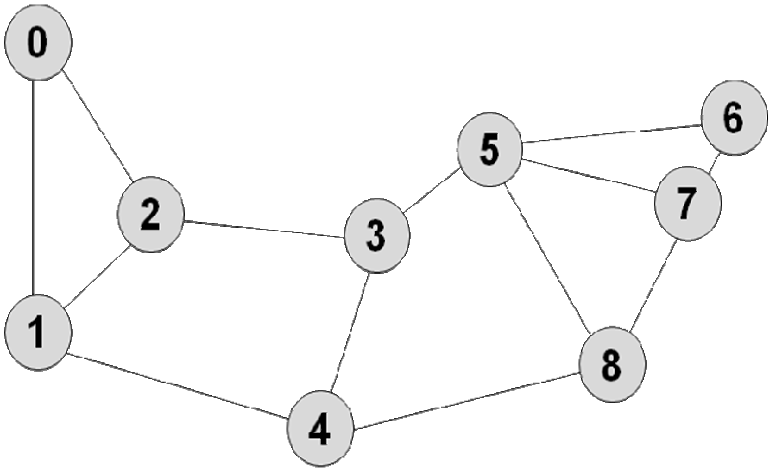


Figure A.9: Internet 2 Network topology.

The distribution of link length for EON and Internet 2 networks are depicted in Figure A.10.

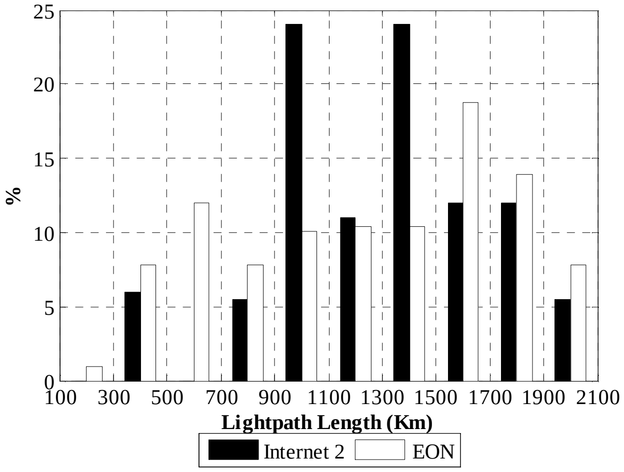


Figure A.10: Link length distribution of EON and Internet 2.

Demand set (Traffic matrix) expressed in Gbps (upper triangle) and the link lengths in Km (lower triangle) of Internet 2 network are summarized in Table A.5.

Table A.5: Demand set and link lengths in Internet-2

	0	1	2	3	4	5	6	7	8
0		16.1	13.8	8.7	8.5	8.5	7.4	6.2	7.0
1	1342		16.3	10.9	14.2	14.2	16.5	8.9	10.5
2	913	1303		11.7	11.2	10.1	7.5	7.5	8.8
3	-	1330	-		16.0	17.8	12.9	12.2	14.8
4	-	1705	-	818		16.9	16.2	12.4	16.3
5	-	-	-	690	-		29.5	18.6	20.0
6	-	-	-	-	-	1400		30.5	22.2
7	-	-	-	-	-	905	278		17.7
8	-	-	-	-	1385	1045	-	700	

Appendix B:

Appendix B: Contributions

B.1 List of Journal publications

[1] **Siamak Azodolmolky**, Panagiotis Kokkinos, Marianna Angelou, Emmanouel (Manos) Varvarigos, and Ioannis Tomkos, “DICONET NPOT: An Impairments Aware Tool for Planning and Managing Dynamic Optical Networks,” Special Issue of Journal of Networks and Systems Management (*Under Review*).

[2] **Siamak Azodolmolky**, Mirosław Klinkowski, Yvan Pointurier, Marianna Angelou, Davide Careglio, Josep Sol´e-Pareta, and Ioannis Tomkos, “A Novel Offline Physical Layer Impairments Aware RWA Algorithm with Dedicated Path Protection Consideration,” submitted to IEEE Journal of Lightwave Technologies (*Accepted for Publication*).

[3] **Siamak Azodolmolky**, Yvan Pointurier, Marianna Angelou, Davide Careglio, Josep Solé-Pareta, and Ioannis Tomkos, “A Novel Impairment Aware RWA Algorithm with Consideration for QoT Estimation Inaccuracy”, IEEE/OSA Journal of Optical Communications and Networking (*Under review*).

[4] **Siamak Azodolmolky**, et al., “Experimental Demonstration of an Impairment Aware Network Planing and Operation Tool for Transparent/Translucent Optical Networks”, IEEE Journal of Lightwave Technologies (*Under review*).

[5] Pablo Pavon-Mariño, **Siamak Azodolmolky**, Ramon Aparicio-Pardo, Belen Garcia-Manrubia, Yvan Pointurier, Marianna Angelou, Josep Solé-Pareta, J. Garcia-Haro, Ioannis Tomkos, "Offline Impairment Aware RWA Algorithms for Cross-Layer Planning of Optical Networks," IEEE Journal of Lightwave Technologies, June 2009.

[6] **Siamak Azodolmolky** (chapter editor), Tibor Cinkler, Dimitris Klonidis, Zsigmond Szilard, Ioannis Tomkos, "Cross-layer optimization issues for realizing transparent mesh optical networks", Towards Digital Optical Networks, COST Action 291 Final report, chapter 6, LNCS 5412, pp. 167-188, 2009.

[7] **Siamak Azodolmolky**, Dimitrios Klonidis, Ioannis Tomkos, Yabin Ye, Chava Vijaya Saradhi, Elio Salvadori, Matthias Gunkel, Kostas Manousakis, Kyriakos Vlachos, and Emmanouel (Manos) Varvarigos, Reza Nejabati, Dimitra Simeonidou, Michael Eiselt, Jaume Comellas, Josep Solé-Pareta, Christian Simonneau, Dominique Bayart, Dimitri Staessens, Didier Colle, Mario Pickavet, "A Dynamic Impairment Aware Networking Solution for Transparent Mesh Optical Networks," IEEE Communications Magazine, May 2009.

[8] **S. Azodolmolky**, M. Klinkowski, E. Marin, D. Careglio, J. Solé-Pareta, and I. Tomkos, "A Survey on Physical Layer Impairments Aware Routing and Wavelength Assignment Algorithms in Optical Networks", Computer Networks (Elsevier), vol. 53, no. 7, pp. 926-944, May 2009, ISSN: 1389-1286 (Available online since December2008).

B.2 List of Conference Publications

[1] **Siamak Azodolmolky**, Marianna Angelou, Ioannis Tomkos, Annalisa Morea, Yvan Pointurier, Josep Solé-Pareta, "A Comparative Study of Impairments Aware Optical Networks Planning Tools,", 7th International ICST Conferece on Broadband Communications, Networks, and Systems, 25-27 Oct. 2010, Athens, Greece, *Under Review*.

[2] Panagiotis Kokkinos, **Siamak Azodolmolky**, Marianna Angelou, Emmanouel (Manos) Varvarigos, Ioannis Tomkos, "Performance Evaluation of an Impairment-Aware Lightpath Computation Engine," *Accepted* for ECOC 2010, Torino, Italy.

[3] Fernando Argaz, Jordi Perello, Marianna Angelou, **Siamak Azodolmolky**, Luis Velasco, Salvatore Spadaro, Panagiotis Kokkinos, Emmanouel (Manos) Varvarigos, Ioannis Tomkos, "Experimental Evaluation of Paht Restoration for a Centralized Impairment Aware GMPLS-Controlled All-Optical Network," *Accepted* for ECOC 2010, Torino, Italy.

[4] F. Agraz, **S. Azodolmolky**, M. Angelou, J. Perello, L. Velasco, S. Spadaro, S.; Francescon, A.; Saradhi, C. V.; Pointurier, Y.; Kokkinos, P.; Varvarigos, E.; Gunkel, M.; Tomkos, I. "Experimental demonstration of centralized and distributed impairment-aware control plane schemes for dynamic transparent optical networks," OFC 2010, PDPD5, March 2010, San Diego, USA.

[5] Yixuan Qin, Yvan Pointurier, Eduard Escalona, **Siamak Azodolmolky**, Marianna Angelou, Ioannis Tomkos, Kostas Ramantas, Kyriakos Vlachos, Reza Nejabati1 and Dimitra Simeonidou, "Hardware Accelerated Impairment Aware Control Plane," OFC/NFOEC 2010, 21-25 March 2010, San Diego, California, USA.

[6] **Siamak Azodolmolky**, Yvan Pointurier, Marianna Angelou, Josep Solé-Pareta, and Ioannis Tomkos, "Routing and Wavelength Assignment for Transparent Optical Networks with QoT Estimation Inaccuracy," OFC/NFOEC 2010, OMM4, 21-25 March 2010, San Diego, California, USA.

[7] I. Tomkos, Y. Pointurier, **S. Azodolmolky**, M. Eiselt, T. Zami, R. Piesiewicz, C.V. Saradhi, M. Gunkel, U. Mahlab, M. Chen, Y. Ye, M. Pickavet, M. Gagnaire, E. Varvarigos, J. Solé-Pareta, R. Nejabati, Y. Qin, and D. Simeonidou "DICONET: future generation transparent networking with dynamic impairment awareness," Book chapter, distributed to the attendees of the Future of the Internet Conference, Prague, Czech Republic, 11-13 May 2009.

[8] **Siamak Azodolmolky**, Yvan Pointurier, Miroslaw Klinkowski, Eva Marin, Davide Careglio, Josep Solé-Pareta, Marianna Angelou, and Ioannis Tomkos, "On the Offline Physical Later Impairment Aware RWA Algorithms in Transparent Optical Networks: State-of-the-Art and Beyond," 13th

Conference on Optical Network Design and Modeling, (Invited paper), Braunschweig, Germany, Feb. 18-20, 2009.

[9] Yvan Pointurier, **Siamak Azodolmolky**, Marianna Angelou, and Ioannis Tomkos, "Issues and challenges in Physical-Layer Aware Optically Switched Network Design and Operation" (Invited presentation), International conference on Photonics in Switching 2009, 15-19 September 2009, Pisa, Italy.

[10] **Siamak Azodolmolky**, Yvan Pointurier, Marianna Angelou, Josep Solé-Pareta, and Ioannis Tomkos, "An Offline Impairment Aware RWA Algorithm with Dedicated Path Protection Consideration," OFC/NFOEC 2009, OWI1, 22-26 March 2009, San Diego, California, USA.

[11] I. Tomkos, **S. Azodolmolky**, M. Angelou, D. Klonidis, Y. Ye, C. Saradhi, E. Salvadori, A. Zanardi, "Impairment Aware Networking and Relevant Resilience Issues in All-Optical Networks," ECOC 2008, Brussels, Belgium.

[12] I.Tomkos, **S. Azodolmolky**, D. Klonidis, M. Aggelou, K. Margariti, "Dynamic Impairment Aware Networking for Transparent Mesh Optical Networks: Activities of EU Project DICONET," vol.1, pp. 6-12, ICTON 2008, Athens, Greece, June 2008.

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