Impairments-aware Routing and Spectrum Allocation in Translucent Flexgrid Networks

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Abstract

Devising a highly flexible and efficient optical transport network with various requirements and features is a main challenge in network design and the connection requests within the network are performed by the Routing and Spectrum Assignment (RSA) algorithms. These algorithms compute the route and allocate the demanded spectrum to the connection in request, where each demanded spectrum is available and sufficient to carry the demanded capacity.

The main feature of the flexgrid optical transport networks is that different capacities for different connection demands can be supported. For instance, two demands, first with the load of 40Gb/s and the second with 400Gb/s can be used with a flexible spectrum allocation. By this means, the inefficiencies and underutilization of the network resources caused by fixed spectrum allocation are eliminated due to the prevention of unused spectrum slots. Hereby the elasticity brings the dynamic adaptation of resources such as spectrum allocation, modulation format and transmission rate.

The flexgrid optical networks split the spectrum into frequency slots and for each application requiring a certain amount of slots, network resources will be used efficiently. For instance, 40Gb/s demands require fewer spectrum than the demands of 400 Gb/s, so the RSA algorithm solves this problem of routing and network resource utilization.

The proposed algorithm aims to obtain a significant performance in routing and efficiency in terms of spectrum allocation, therefore, the work presented in this thesis brings out a new RSA algorithm considering physical impairments in an optical network and deploying regenerators. The algorithm consists of two phases. In the first phase, an auxiliary graph is created, which only presents the connectivity from the source node to the regenerators and the intermediate nodes having a shortest path. K-shortest path algorithm is applied on this auxiliary graph, in order to determine the feasible routes. It has to be noted that each link in the shortest paths represent a lightpath between the two nodes. Thus,

intermediate nodes might exist between these two nodes and the shortest path will be determined on the real graph in the second phase. The purpose of the auxiliary graph is to select the path with minimum number of regenerators.

The second phase involves finding the shortest path for each lightpath. Since k-shortest paths are determined on the auxiliary graph, they are expanded to the real lightpaths and at the end, the route with least number of regenerators and minimum length is selected.

The proposed algorithm is evaluated by analyzing different performance criterions that are important in an optical transmission networks and compared with previous RSA algorithms which do not utilize regenerators and do not consider physical impairments.

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Chapter 1

Introduction

1.1 Motivation

The steady increasing bandwidth demand is fostering the development of technology able to deal with optical signals of 400Gb/s, 1Tb/s and beyond. Flexgrid has become the evolving technology in optical communications, providing a flexible and efficient solution to mix signals of different bandwidth. To transport these signals, efficient management of the spectrum becomes is required to compute the route and allocate spectrum for optical connections and set them up over the optical network.

Although advanced modulation formats are being developed, the maximum reach of optical connections conveying that huge bit rates is limited, e.g. 400km, as a result of physical layer impairments. Therefore, regenerators need to be installed in the network to extend that reach. The presence of regenerators transforms an optical network from transparent to translucent; an end-to-end connection might be thus consists of several stitched lightpath segments.

Compared to transparent networks, translucent networks thus provide regeneration at intermediate nodes to degraded signals. With 3R regeneration, the signal is reproduced and might be transmitted with a different modulation format or wavelength. However, regenerators are expensive components, so their use must be limited to prevent network cost to increase. Therefore, efficient routing and spectrum allocation (RSA) algorithms that take into account impairments and minimize the use of regenerators becomes clearly necessary. Those impairments-aware (IA) RSA algorithms must ensure a certain level of Quality of Service (QoS) and to eliminate their effects on the chosen route in the network.

1.2 Goal of the thesis

The main objective of this thesis is to develop an algorithm for impairment aware RSA that deploys minimum number of regenerators in the optical transmission network and selects the route with minimum number of hops.

Chapter 2

Background in optical networks

In this chapter we introduce the concepts and technologies that serve as a start point for this master thesis. Firstly, we briefly explain the basics of optical networks: the fixed grid and flexgrid technologies are introduced. In addition, we define physical impairments are defined. Next, optical networks are presented starting from the basic optical nodes. The optical network is modeled as a layered network defining reference points and connections. Finally, we differentiate between static and dynamic traffic in optical networks, and present the control plane as the basis for automated connection provisioning.

2.1 Optical Technology

An optical network is a network composed by optical nodes that are connected using optical fibers. Data entering the network in the electrical domain is converted to the optical domain and then transmitted as an optical signal. In each intermediate node, signals are transparently switched and transmitted towards the destination node, where the signal is converted back to the electrical domain..

2.1.1 Wavelength Division Multiplexing

The Wavelength Division Multiplexing (WDM) technology allows transmitting different data flows on different optical wavelengths. Most WDM systems currently use the frequency region around 1550 nm, since this is one of the frequency regions where the signal attenuation reaches a local minimum. Fig. 2-1 shows an example of the WDM technology.

WDM systems with channel spacing ranging from 12.5 GHz to 100 GHz have been specified [G.694.1]. With that technology, the number of optical wavelength channels being multiplexed onto a single fiber ranges 50-400. When such a large amount of channels can be transported by the WDM system, the term Dense Wavelength Division Multiplexing (DWDM) is used, in contrast to Coarse Wavelength Division Multiplexing (CWDM), which is considered for the metropolitan network and multiplexes a limited number of wavelengths onto a single fiber.

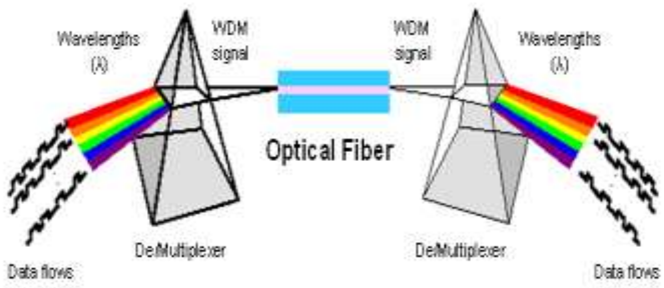


Fig. 2-1: WDM Technology

Light emitters (usually semi-conductor lasers) are key components in any optical network. They convert the electrical signal into a corresponding light signal, on a single wavelength, that can be injected into the fiber. Besides, a DWDM system uses a multiplexer at the transmitter to multiplex the different wavelengths together in a bundle, and a demultiplexer at the receiver to split them apart. An optical fiber transmit optical signal through long distances. However, the power of the signal is reduced when it propagates over distance, this is called attenuation. The receiver sensitivity indicates the minimum power required to detect the incoming signal. In order to compensate for the effect of attenuation, the optical signal can be amplified within the optical domain.

When the optical signal travels through an optical fiber it is also distorted by the effect of dispersion, which modifies the optical pulse duration. This may lead to inter-symbol interference. Two important types of dispersion can be compensated: the Chromatic Dispersion (CD) and the Polarization Mode Dispersion (PMD). Thus, regenerators allow compensating for dispersion, by converting the optical signal to the electrical domain.

Today, on a typical 40 channel DWDM system transporting 10Gbit/s per wavelength, the maximum distances that can be transmitted without regeneration are about 2000 km [PePe04]. Moreover, new modulation formats, currently in a pre-commercial phase, will increase both bandwidth and distance [Wi08].

SONET/SDH technologies, and more recently Optical Transport Network (OTN) [G.709], standardize transmission frame formats, including a set of overhead bytes.

Although paths are end-to-end, section overhead bytes are ended and processed at every intermediate node. Adjacent nodes communicate each other using those bytes. On the contrary, in all-optical or *transparent networks* optical connections are established between end nodes, assigning them a specific optical channel, without any intermediate electronic processing. In such transparent optical networks, a node cannot communicate with any adjacent.

2.1.2 Optical modulation formats

The optical signals that are aimed to be transmitted from a source to a destination node are first modulated by using several modulation formats. As the purpose of the modulation is to transmit information by utilizing the properties of a periodic waveform, optical modulation uses a beam of light in order to modulate signals. Therefore, an optical modulator is used for modulation and the beam may be transmitted over free space or propagated through an optical waveguide. Modulation schemes are categorized depending on the physical properties of the modulated signal, such as amplitude modulators, phase modulators, polarization modulators.

Phase shift keying (PSK) and Quadrature-Amplitude Modulation (QAM) schemes principally require different phase and amplitude levels for different information bits to be transmitted. Their constellation schemes are given in Fig. 2-2. M-ary phase shift-keying (M-PSK) or M-ary Quadrature-Amplitude Modulation (M-QAM) involve M different states of signal, for instance, M-PSK consists of M phases which may transmit 2^M different signals carrying information. These modulation schemes present different constellation schemes and lead to different spectral efficiencies, having the similar constellation diagrams of PSK and 16-QAM.

Considering a given connection request d asking for $B(d)$ Gb/s, the spectral resources that need to be allocated are a function of the spectral efficiency (B_{mod} in b/s/Hz) of the chosen modulation format and the slot width, denoted as $F(S)$ in GHz. For instance, considering the 16-QAM ($B_{16\text{-}QAM}$=4 b/s/Hz), it needs half spectrum width than QPSK (B_{QPSK}=2 b/s/Hz) to transmit the same bit rate. On the other hand, 16-QAM has worse receiver sensitivity than QPSK so both the length in hops, which entails cascade filters, and the distance of optical connections using the 16-QAM modulation format is limited. Fig. 2-3 presents that different M-ary QAM and PSK modulation schemes have different optical reach and spectral efficiencies. Therefore, it has to be noted that the modulation format is a constraint on the reach of the optical signal and the total length of the hops.

However, in optical transmission, M-QAM and M-PSK can be implemented by using a local-oscillator (LO) to accomplish heterodyne or homodyne down conversion, balanced optical receivers and appropriate electrical-domain detector [mod.and.det.tech.COTA.6-06]. In this work, mainly 2 modulation schemes are utilized: QPSK and 16-QAM.

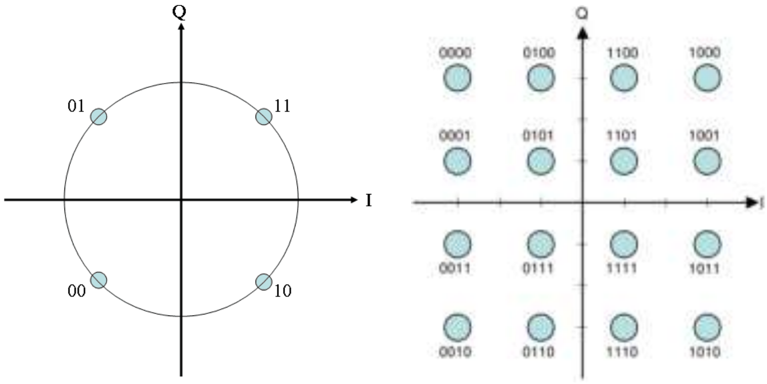


Fig. 2-2: QPSK and 16-QAM modulation constellation diagrams

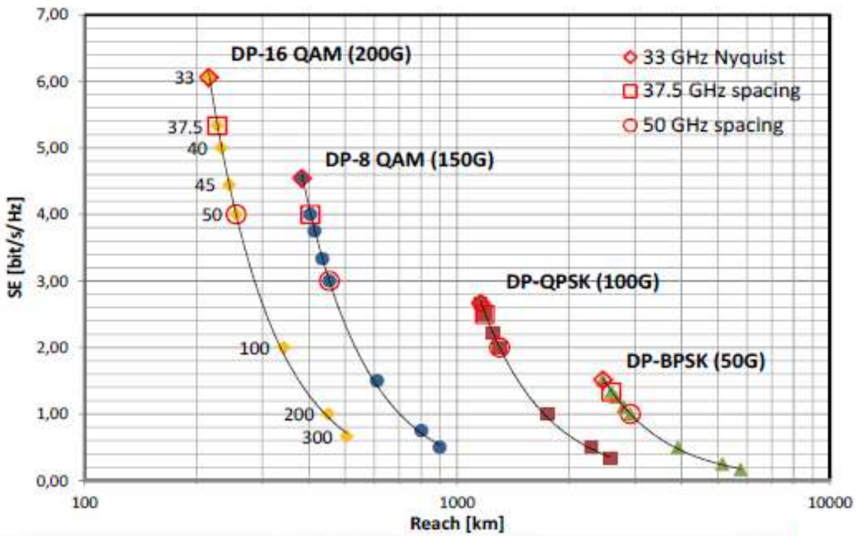


Fig. 2-3: Modulation formats and spectral efficiencies of QPSK and QAM

2.1.3 Flexgrid

The Flexgrid technology [Ji09], [Ji10], provides higher spectrum efficiency and flexibility in comparison to traditional WDM-based networks. Thanks to this flexible technology, a flexgrid optical network can adjust to varying traffic conditions over time, space and bandwidth, thereby creating a network scenario where wavelength channels are both switched and dimensioned (bitrate/reach/signal bandwidth) according to temporary traffic requirements. To this end, traffic demands are assigned a given number of frequency slots (FSs) according to their requested bit-rate, the selected modulation technique and the considered frequency grid (i.e., the slot width) [Ji10]. Note that this is in contrast to WDM-based networks where demands use one FS.

Without loss of generality, B_{mod} being the spectral efficiency and $F(S)$ being the slot width in GHz,, we compute the amount of contiguous slots required by connection request d, denoted as $S(d)$, as in [Ji10]:

$$S(d) = \left\lceil \frac{B(d)}{B_{\text{mod}} \cdot F(S)} \right\rceil \tag{2.1}$$

It must be mentioned that the previous equation tends to under-estimate the number of FSs required, as it assumes that *B(d)* consists only of payload data. However, in general, this is not the case, as different overhead data (e.g., around 10% extra) may be required. Such overhead may vary according to the modulation format selected. For instance, in OFDM-based systems, overhead symbols are required to avoid inter-symbol interference. Additionally, the selection of the modulation format may depend on each particular demand bit-rate. These issues, however, are left out of the scope of this thesis.

Table 2-1 Contiguous slots required per connection request as a function of the slot width and the used modulation format.

	Requested bit rate (*B*(*d*))							
Slot width (*F*(*S*))	**10 Gb/s**		**40 Gb/s**		**100 Gb/s**		**400 Gb/s**	
	QPSK	16-QAM	QPSK	16-QAM	QPSK	16-QAM	QPSK	16-QAM
50 GHz	1	1	1	1	1	1	4	2
25 GHz	1	1	1	1	2	1	8	4
12.5 GHz	1	1	2	1	4	2	16	8
6.25 GHz	1	1	4	2	8	4	32	16

2.1.4 Physical Layer Impairments

Physical layer impairments are those effects that can affect or degrade the optical information on lightpaths and can be classified into linear and non-linear [Az09]. Linear impairments such as fiber attenuation, amplifier spontaneous emission (ASE) noise, chromatic dispersion (CD) (or group velocity dispersion (GVD)), and polarization mode dispersion (PMD) are independent of the signal power and affect each of the wavelengths individually. On the other hand, nonlinear impairments affect not only each optical channel individually but they also cause disturbance and interference between them. The most important nonlinear effects are: self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [Sa09.1].

In this thesis, however, we consider only linear impairments, since they are predominant in flexgrid networks. Therefore, the longer the path an optical signal is transported on, the more amplifiers are needed to compensate the power loss due to the fiber and node attenuations. The increased number of amplifiers makes the ASE noise a significant impairment factor to the signal quality. The Optical Signal to Noise Ratio (OSNR) is used to capture the impact of the ASE noise [Hu05]. Fig. 2-4 illustrates the computation of the estimated OSNR at the receiver of an optical connection. The signal traverses $N - 1$ links each allocating a different number of amplifier spans.

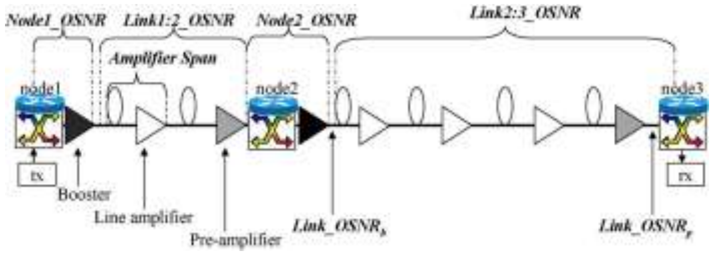


Fig. 2-4: Contributors for the path OSNR computation (reproduced from [Ma10])

To estimate the OSNR level at node N, the following assumptions are made:

- The pre-amplifier (at the input port of a node) and the line amplifier have the same characteristics, but the booster amplifier (at the output port of the node) has, in general, different characteristics such as the noise figure.
- For the computation of the OSNR in a lightpath involving nodes (including source and destination nodes) only the first $N - 1$ nodes contribute to the OSNR estimation. The destination node is not considered since it is not entirely crossed by the lightpath.
- The maximum OSNR level (i.e., $OSNR_{\max}$) of a Label-Switched Path (LSP) is the OSNR level at the optical transmitter, that is, at either the source node or after using a 3R regenerator at an intermediate

As described in [Ts08], there are two components contributing to the OSNR level estimation: the *Link_OSNR* that considers the total ASE noise induced by all the (pre- and line) amplifier spans of a link (e.g., *Link1:2_OSNR* in Fig. 2-4) and the *Node_OSNR* which considers the ASE noise caused by the node booster amplifier. Thus, the estimated OSNR (*Total_OSNR*) for a transparent segment traversing links and nodes is given by:

$$Total\_OSNR_N = \frac{1}{\left(\sum_{j=1}^{N-1} \frac{1}{Link\_OSNR_j} + \sum_{j=1}^{N-1} \frac{1}{Node\_OSNR_j} \right)} \tag{2.2}$$

where the $Link\_OSNR_j$ and the $Node\_OSNR_j$ are the OSNR for the j^{th} link and node, respectively. It is worth noting that the expression in Eq.2.1 is simplified and holds if the amplifier's gain is automatically controlled in order to basically maintain a constant optical power per wavelength channel at the output of the amplifiers.

In addition to the ASE noise, other accumulated impairments such as the PMD, CD and the nonlinearities may impact on the signal quality of the transparent segments. These impairments are integrated into the constraint model as OSNR penalties [St01], [Pa08], [Le09], [Cu08], [Ts08], [Sa09.2]. To this end, the degradation caused by these physical impairments needs to be kept within defined acceptable ranges or constraints.

The TE Link OSNR consists of two OSNR values (in dB) that allow computing the *Link_OSNR*, namely, the $Link\_OSNR_b$ and the $Link\_OSNR_p$ (see Eq. 2.3). Thus, the *Link_OSNR* can be computed according to the next formula using the OSNR levels at both ends of the link, i.e., $Link\_OSNR_b$ (after the booster amplifier of the link) and the $Link\_OSNR_p$ (after the pre-amplifier of the same link) in Fig. 2-4.

$$Link\_OSNR = \frac{1}{\frac{1}{Link\_OSNR_p} - \frac{1}{Link\_OSNR_b}} \tag{2.3}$$

2.2 Optical networks

2.2.1 Optical Network topology

The first optical systems were point-to-point systems. The introduction of Optical Add/Drop Multiplexer (OADM) in the transport networks allows them to be configured in ring-based topologies, similar to traditional synchronous digital hierarchy (SDH) [G.707] networks. An OADM allows dropping a specific wavelength out of the bundle of DWDM-multiplexed signals, and adding another channel on the same wavelength (Fig. 2-5a)

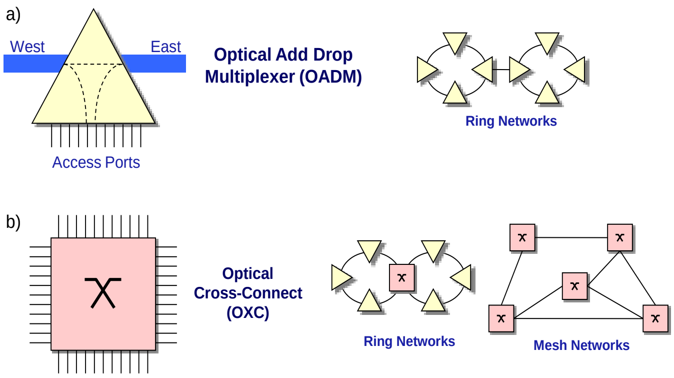


Fig. 2-5: Optical nodes and topologies

The introduction of sophisticated optical devices such as Wavelength Selective Switches (WSS) [TsHu06] made possible to build evolved OADM architectures and optical cross-connects (OXCs), the key element to build optical mesh-based networks (Fig. 2-5b) [RoCo08].

The nodal degree (d) of a node is the number of links incident on the node (number of DWDM ports). In the rest of this thesis we use the term OADM for optical nodes with $d = 2$, and the term OXC for optical nodes with $d \geq 2$.

Ring-based networks present lower capacity efficiency than mesh networks; mesh networking allows connections to be routed over shorter paths. In this regard, mesh-based networks have been extensively used in packet-based networks due to their high efficiency and flexibility. In practice, however, the cost per DWDM port in OXCs is much higher than in OADMs.

Similarly to WDM-based networks, in flexgrid networks bandwidth-variable wavelength selective switches (BV-WSSs) are one basic component enabling the design of bandwidth-variable optical cross-connects (BV-OXCs). In addition, bandwidth-variable transponders (BV-Ts) can be configured to source demands of several bit-rates.

While BV-Ts may work under both single- and multi-carrier advanced modulation formats such as QPSK, QAM, and O-OFDM [Ji10], BV-WXCs can be assembled using existing devices like the *WaveShaper* programmable optical processor [Finisar].

2.2.2 Layered networks

In general, a telecommunication network is typically split into two segments: the transport or core network and the access network. The transport network links the nodes in the important cities with each other. The access network is the part of the network allowing the individual customers to connect to the nearest network node. Between the transport and the access network, we can also find a metro network, expanding over a big city or an entire region. Nonetheless, in the near future ring-based networks will remain more extensively deployed than mesh networks.

Regarding the network model, each network layer holds a twofold role, namely a server role to the client layer above it, as well as a client role to the network layer below it. In brief, a sub-network describes the capacity to associate a set of connection points (CP) to convey the so-called "characteristic information". With such objective, two possible kinds of connection are defined. A *link connection* is a fixed and inflexible connection between two CPs. Conversely, a *Sub-Network Connection* (SNC) is a flexible connection that may be set-up and released by either the control or the management plane. As the result, a *network connection* is a concatenation of *sub-network* and *link connections* delimited by a Termination

Connection Point (TCP) pair. Correspondences between ITU-T and IETF terminology can be found in [RFC-4394, RFC-4397].

Through the defined reference layered network architecture, the optical network can be modeled as a two-layered transport network. The first layer is represented by the DWDM TE links and optical network ports, whereas the second layer is represented by the different wavelength channel data links and access optical ports.

A two-layered 3-node all-optical network is shown in Fig. 2-6a. In such scenario, link connections associate CPs at remote neighboring nodes. Those link connection sets are bundled into network connections between remote TCPs, which respectively represent TE links and optical network ports.

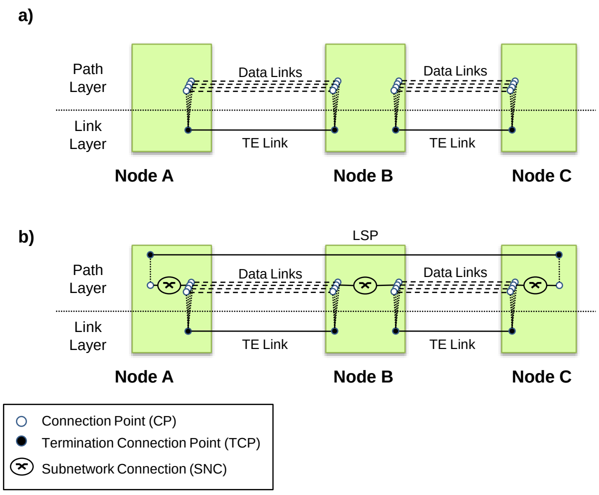


Fig. 2-6: Example of a layered network architecture

Let us suppose now, that a path is set-up between ingress node A and egress node C (Fig. 2-6b). The incoming client signal at the optical node A is adapted and cross-connected by an SNC to an outgoing CP. This CP is, in turn, connected through a data link to an incoming CP in the neighbor. At the intermediate node B, a SNC binds incoming and outgoing CPs, which should be mapped to the same wavelength in case that no wavelength converter is used (wavelength continuity). As soon as the signal reaches the destination node C, this one is cross-connected, adapted and sent to the optical access port.

2.2.3 Transparent, Translucent and Opaque Networks

Transparent Networks: In transparent optical networks, signals are allowed to avoid electronic signal processing at intermediate nodes. However, the optical signal quality decreases, while it goes through numerous optical components through its optical connection (i.e., *lightpath*) from its source to destination. These degradations are caused by optical-fiber nonlinearities; chromatic and polarization-mode dispersion; noise accumulated due to the ASE noise from optical fiber amplifiers; effects of non-flat gain profile and gain saturation in fiber amplifiers; cross-talk introduced at cross connects. To surpass these impairments, "long-distance" lightpaths may require *signal regeneration*, at one or more intermediate locations in the network. Signals are regenerated through an opto-electronic conversion and afterwards through an electro-optic conversion, or completely in the optical domain.

Opaque Networks: In opaque optical networks, a single optical hop of a lightpath never deploys more than one physical fiber link in the network.

Translucent Networks: As an alternative to the opaque and transparent networks, translucent networks are proposed. In translucent networks, a signal from the source traverses through the network as further as possible until its quality degrades, by that means requires the signal to be regenerated at an intermediate node. The same signal could be regenerated various times in the network before it arrives to the destination [Ra99].

Recently, optical networks are evolving from traditional *opaque* infrastructures towards *transparent* infrastructures [Ra99]. An opaque network performs reamplifying, reshaping, and retiming (3R) regeneration for every wavelength channel at each node traversed by the connection. This allows regenerating the optical signal and improves the transmission quality. On the other hand, transparency implies that signal remains within the optical domain from the source to the destination node. Thereby, transparency eliminates the optical-electronic-optical (OEO) conversions or 3R regenerators at the intermediate nodes. This yields important benefits such as freedom on the bit rates and data formats of the transported signals, elimination of the well-known electronic bottleneck and reduction of both network cost and power consumption [Po08]. The key enablers to deploy transparent or all-optical networks are, on the one hand, the advances on relevant optical signal functions (e.g., amplification, filtering, and dispersion compensation) and, on the other hand, the availability of network nodes capable of routing and switching in the optical domain (e.g., ROADMs and OXCs). Such an all-optical switching network is referred to as a Wavelength-Switched Optical Networks (WSON).

Nevertheless, due to the lack of electronic regeneration, two constraints impose fundamental limitations to transparent WSON: the wavelength continuity constraint (WCC) and the optical physical impairments [Ya05]. The WCC implies that a lightpath is subject to use the same wavelength on each link along the route. This restriction raises important challenges at the time of computing and establishing lightpaths, specifically to achieve an acceptable network performance in terms of connection blocking probability.

In the evolution from opaque networks towards transparent WSON, *translucent* networks are considered as an intermediate step [Ya05]. This infrastructure uses a set of sparsely but strategically 3R regenerators placed throughout the network to do signal regeneration [Sh07]. Therefore, a translucent network is a cost-efficient infrastructure that aims at attaining an adequate trade-off between network construction cost, mainly due to the high cost of 3R regenerators, and the service provisioning performance, adequate end-to-end quality of transmission (QoT).

2.2.4 Static and dynamic traffic

Two different approaches can be considered for planning and operating communications networks: static and dynamic traffic scenarios [Gu04]. In static traffic scenarios, no changes are considered in the connections established during the working period of the network. Thus, the information about the *client demands* to be served, i.e. the source and destination nodes and the required bandwidth, is known in advance. Since the routing of those demands can be done before the network begins to operate and no changes are allowed during the working time, the optimality of the network planning is always kept. When the network resources are limited and some demands cannot be established, we can define the *blocking rate* as the proportion of those refused demands over the total.

On the contrary, in dynamic traffic scenarios the demands are not known in advance and the connections are continuously set up and dropped. Thus, client requests arrive to the network following a certain probability distribution function. Moreover, connections remain active during a certain period of time, i.e. the service time, which can be also modeled by another probability function. For sake of clarity, we will use client request instead of client demand in the case of dynamic traffic scenarios.

The most common model for dynamic traffic is the Erlang model [ITU05], where arrivals are modeled following a Poisson probability function identified by the mean time between two consecutive arrivals, namely inter-arrival time (*iat*).When Poisson arrivals are assumed, the service time follows an exponential probability function identified by the mean holding time (*ht*). Note that the inverses of iat and *ht* are called inter-arrival rate (λ) and service rate (μ), respectively. The traffic intensity or the offered load can be computed as *ht*/*iat* or, alternatively, λ/μ and its unit is the erlang. Thus, the traffic intensity represents the mean number of established connections in a network at a random time instant. The source and destination of the demands are also random variables and they can follow several models, e.g. uniformly distributed, proportional to the distance between nodes, etc.

When a connection request arrives to the source node, some routing procedure is executed to find an available route over the network. If routes are pre-computed and remains invariable independently of the load and the availability of resources of the network, the procedure is called static routing. On the contrary, when the route is found by means of some routing algorithm executed at the request instant, thus considering the current status of the network, the procedure is called dynamic routing [Za02]. In both cases, when the network does not contain enough free resources to establish a connection request, the connection is blocked. Then, we can define the blocking probability as the probability to refuse a connection request at a random time instant. To compute the blocking probability of a network during a period of time, the amount of refused connections is divided into the amount of connections requested. The blocking probability of a network is used to define and quantify the Grade of Service (GoS) of a network.

2.2.5 Automatically Switched Optical Network

An Automatically Switched Optical Network (ASON) [G.8080] is an optical transport network that has dynamic connection capability. This functionality is accomplished by using a control plane that performs routing, signaling and resource discovery.

The ASON architecture (Fig. 2-7) defines three different planes which exchange information through a set of defined interfaces:

- The transport plane represents the functional resources of the optical network which convey user information between locations. It includes optical nodes and optical fibers, and is able to measure parameters to characterize the connections state, detecting failures, etc.
- The control plane is in charge of the resource management, routing and connection signaling. The objective is to define an intelligent control plane able to create, modify and release connections automatically.
- The management plane provides the network management functions (FCAPS): Failure management, Configuration management, Accounting, Performance management, and Security [M.3400].

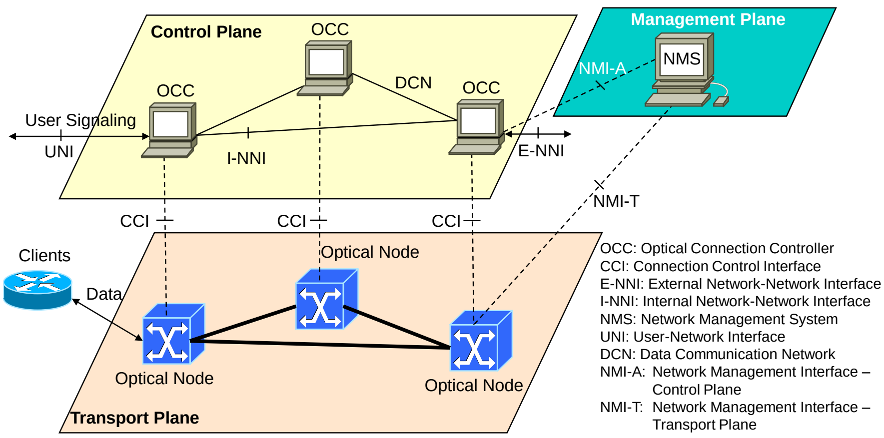


Fig. 2-7: The ASON architecture

2.3 Control plane

2.3.1 Generalized Multiprotocol Label Switching (GMPLS)

Within the Internet Engineering Task Force (IETF), the Common Control and Measurement Plane Working Group (CCAMP) [CCAMP] is leading the standardization of a framework known as Generalized Multiprotocol Label Switching (GMPLS) [RFC-3945]. GMPLS is a technology that provides enhancements to Multiprotocol Label Switching (MPLS) to support network switching not only at the packet level but also at time slot, wavelength, or even fiber level. In other words, GMPLS provides several extensions to the protocols already took place in MPLS technology, in order to expand its usage in various types of switching: packet switching, TDM switching, Lambda switching and space switching.

The terminology used by the IETF for the ITU term network connection is Label Switched Path (LSP). In the rest of this thesis we use the term LSP for the sake of brevity.

GMPLS provides a control plane in support to optical networking. Nevertheless, GMPLS is based on Traffic Engineering (TE) extensions of:

- RSVP-TE signaling protocol [RFC-3209, RFC-3473], and
- intra-domain link-state OSPF-TE routing protocol [RFC-3630].

Moreover, the use of technologies like DWDM implies that we can now have a very large number of parallel links between two adjacent nodes (hundreds of wavelengths, or even thousands of wavelengths if multiple fibers are used). To solve this issue the concept of link bundling was introduced. Moreover, the manual configuration and control of these links, even if they are unnumbered (links that do not have IP addresses), becomes impractical. The Link Management Protocol (LMP) [RFC-4204] was specified to solve these issues.

Regarding the key elements of the control plane, Optical Node Connection Controller (OCC) has an important role. The OCC architecture includes the components described in [G.8080]. Specifically, it contains:

- the *Call Controller*, which is responsible for admission policies. Connection requests from clients arrive through the UNI interface [RFC-4208],
- the *Connection Controller* component, which is responsible for connections set-up, modification and tear down. It exchanges RSVP-TE messages,
- the *Routing Controller* component, which is responsible for routes computation. It exchanges OSPF-TE messages, and

- the *Link Resource Manager*, which is responsible for local data-link and TE link resources. This component uses the Connection Controller Interface (CCI) interface to manage the local OXC and exchanges LMP messages.

2.3.1.1 **OSPF-TE Protocol**

GMPLS uses a routing protocol called OSPF-TE, which is used to discover and update the network topology.

This protocol is used to maintain the current state of the network at each moment of sending information from the resources to all network nodes. Thus, each node uses OSPF-TE protocol while creating new connections that allocate resources, in order to inform the other nodes about the changes or reservations that are made.

2.3.1.2 **RSVP-TE Protocol**

The RSVP-TE protocol is responsible for the signaling route that the traffic can assure a certain Quality of Service (QoS) to the user. In order to obtain this QoS, there will be a resource reservation along the nodes that are to be traversed.

When a client application requests a specific QoS, RSVP is responsible for meeting the requirements in each node along the path.

This protocol consists of the following types of messages:

- Hello: For detection of failures.
- Notify: For rapid notification of the failures.
- Path: To create the connection. The source node that sends the data, sends messages periodically to the path for each data stream originated.
- Resv: Responsible for reserving resources for the connection from the source node to the destination node. When Resv arrives at the source, the connection is established.
- PathErr and ResvErr: They are responsible for notifying the source of an error that occurs in Path and Resv respectively, which are received at a node. They indicate that the errors have occurred and where exactly they have occurred.

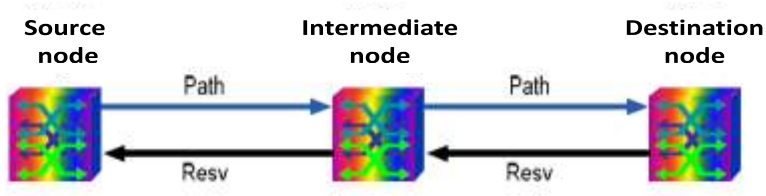


Fig. 2-8: RSVP-TE protocol messages that are exchanged between nodes, in order to create a connection

2.3.2 Path Computation Element (PCE)

IETF supports the PCE architecture, which is a network entity responsible for path computation process. The computation process is performed after collecting link-state information of the network nodes after a certain demand of a client. As the path computation clients (PCC) demand path computations, there occurs an interaction among PCC and PCEs via PCE protocol (PCEP).

PCE accomplishes the path computation on its own layer and has full visibility and updated information of the available resources in the network. The computation of a path requires the network topology and current Traffic Engineering (TE) information, so that the internal Traffic Engineering Database (TED) including these information is accessed by the PCE.

2.4 Conclusions

In this chapter, the key elements of the optical technology were introduced. Furthermore, not only Wavelength Division Multiplexing and Flexgrid networks, but also the optical modulation formats used in optical transmission and the physical layer impairments occurring in optical networks were covered.

Chapter 3

Routing and Shortest Path Algorithms

In this chapter, we introduce the fundamental concepts of routing and shortest path algorithms that contain essential information of optical networks to understand the purpose of this master thesis. Firstly, we concisely present the basics of the graph theory. Next, routing algorithms are explained by initially introducing graph terminology and continued with shortest path algorithms. Finally, the key issues of path computation are stated in two sections of Routing and Wavelength Assignment and Routing and Spectrum Allocation.

3.1 Graph theory

A *graph* or *topology* $G(V,E)$ consists of a set V of nodes or vertices and a set E of edges or links, being the degree of a node defined as the number of edges incident with that node [Ha94]. As a measure of the mesh degree, the *average nodal degree* (δ) is defined as follows:

$$\delta = \frac{2 \cdot |E|}{|V|} \tag{3.1}$$

where $|N|$ and $|E|$ represent the number nodes and links, respectively. Note that δ ranges from 2 for the case of a ring topology to |N|-1 for a full mesh topology.

Given a graph, a path can be defined as of a sequence of nodes that can be sequentially visited without repetitions from a source to a destination following a connected set of links. Several relations can be defined between two different paths with the same source and destination. Thus, two paths are distinct if exist at least one link different between them. When all the links are different, the paths are link-disjoint, whereas if all the intermediate visited nodes are different the paths are node-disjoint.

Regarding paths distance, we can define the shortest path between each pair of nodes as the minimum number of visited links needed to connect both ends. Thus, the average shortest path (h) computes the mean value of all these shortest paths. In addition to this, the diameter is the longest shortest path and the radius is the minimum eccentricity in a node, which can be computed as the maximum distance between this node and any other in the network.

Among different characteristics which allow classifying graphs, we focus on the definition of planarity and connectivity. A graph is planar if and only if it can be drawn on the plane in such a way that no edges cross each other. A graph is connected if exists, at least, one path between each pair of nodes. More generally, a topology is k-connected if exists, at least, k link-disjoint paths between every pair of nodes.

Finally, Fig. 3-1 shows the *homeomorphic graph* of the depicted source topology. This graph is built by removing the nodes with degree equal to two from the original topology [Gr03].

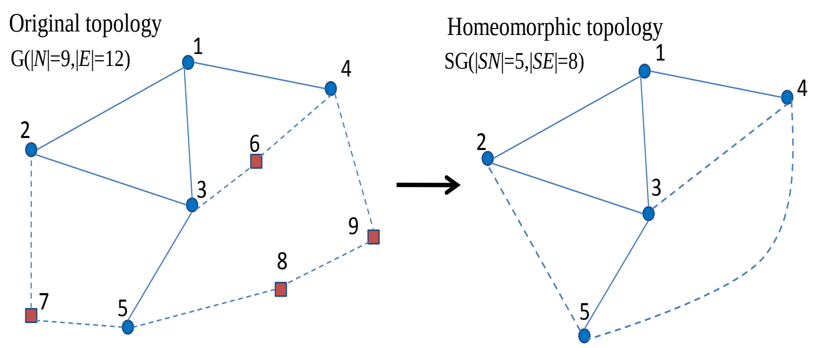


Fig. 3-1: Homeomorphic topology construction

3.2 Routing algorithms

This topic will explain relevant concepts and definitions of the graph theory, discuss various properties that are applicable to the graphs. Furthermore, it will discuss different routing algorithms that are used to calculate the minimum routes, which can be simple or disjoint.

3.2.1 Graph theory related transport networks

Transportation networks are represented as a set of nodes and the connections between them. Typically, nodes are buildings or enclosures of equipment and connections including representative facilities of transmission or cable ducts.

A graph G = (V, E) consists of a finite set of vertices $V = \{v_1, v_2, ...\}$ and set of edges $E = \{e_1, e_2, ...\}$ such that each edge in E connects a pair of vertices V. When we refer more directly to the context of a network of transport, however, the terms node and link (or span) are used, as well as their corresponding sets N and E instead of vertices and edges.

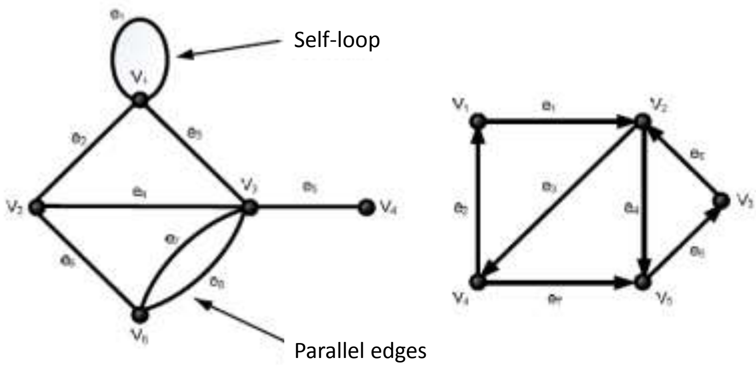
The vertices $\{u, v\}$ of a graph are adjacent if they are joined by an edge $e = \{u, v\}$ and E. This edge is incident to the vertices u and v, which are also known as the end vertices of e. Similarly, two edges are adjacent if they are incident to a common vertex. A graph is *simple* if it has no parallel edges or loops. A circle itself is an edge that begins and ends at the same vertex. A graph having more than one pair of edges which are parallel between vertices are called *multigraph*. The name W_{uv}, associated for each edge $\{u, v\}$ in the graph, corresponds to the weight of the edge $\{u, v\}$. In networks, these weights often represent transport cost, distance and capacity utilization. A graph where the weight of the edge represents the graph capabilities and the problems related with the determination of capacity (or a solution given to the problem of routing capabilities) are called capacity problems.

Furthermore, the data routing problems typically adopt a view of a simple graph, while many problems of transport networks require graph capabilities or a multilevel representation. Transport networks in the graph of the network refer only to the network topology of nodes and links. A variety of graph weighs can be used for routing problems depending on the metric observed in shortest paths.

In fact, as aforementioned, flexgrid optical networks divide the available optical spectrum into a set of FSs. Therefore, an additional set S representing the set of FSs available in each link $e \in E$ is needed for such networks.

Moreover, an edge is directed if the order of vertices {u, v} changes the properties of the edge. A directed edge is drawn with a line and an arrow indicating the direction. A graph is non-directed if none of its edges are addressed. Usually, the networks in which transmission is bidirectional for each link are simply treated as non-directed graphs. Thus, for a transport network, non-directed graph and a bidirectional graph are equivalent concepts.

In graph theory, a path is any sequence of adjacent edges in a graph. For example, P = $\{(v_1, v_2), (v_2, v_3), ..., (v_{k-2}, v_{k-1}), (v_{k-1}, v_k)\}$. The vertices v_1 and v_k are respectively known as the source and destination of the path. The number of edges in the path, k-1, is called path length. If all the vertices of the path are different, it is called a route. The origin node is known as the source node and the ending node is the destination node.



(a) undirected graph (b) directed graph

Fig. 3-2: Terminology of the graphs

A path is closed, if the source and destination vertices are the same and usually it is called a closed path or a cycle. Routes of cyclic signals are highly common to keep the protection. A graph that has all the vertices connected and passes only once for each cycle is called a Hamiltonian graph. A cycle that crosses all edges of the graph exactly once (but a vertex can be visited more than once) is called Eulerian cycle and an Eulerian graph is a graph containing an Eulerian cycle. Eulerian and Hamiltonian cycles are illustrated in Fig. 3-3

(a) Hamiltonian cycle, visiting all the nodes once, but all the links

(b) Eulerian cycle, visiting all the links once, but some nodes can be revisited

Fig. 3-3: Hamiltonian and Eulerian cycles

Eulerian graphs are easily identifiable in polynomial time, but the corresponding question "Does the graph G contains a Hamiltonian cycle?" is an NP-complete decision problem. However, Hamiltonian cycles are more likely to exist in highly connected networks. It leads to the fact that any graph of N nodes where each node has a degree of $\geq N/2$ is Hamiltonian [Ga10].

A graph $G'=(V', E')$ is a subgraph of G if $V' \subseteq V$ and $E' \subseteq E$. Two vertices (not necessarily neighbors) are said to be connected if there is a path between them in G. A non-directed graph G is connected, if there is at least one route between every pair of vertices in G.

A plane graph is a graph in which vertices are points in an R×R plane and their edges are lines in the plane, which don't have intersection points on their vertices. In practice this means that it is possible to draw the graph on a flat page and that the edges do not cross.

A graph is two-edge connected if it has at least two disjoint routes between each pair of vertices and it is bi-connected if there are at least two vertices in disjoint routes between each pair of vertices. Properties of a connectivity of a graph are important for the transport because in order to prevent failures, at least two edges should be topologically connected to protect or restore failed links. The characteristics of a bi-connected network are easily recognized by visual inspection. Any two-connectivity or bi-connectivity is convenient for the network design against link failures but bi-connectivity is preferable to avoid having a single node, which splits the network into two disconnected parts.

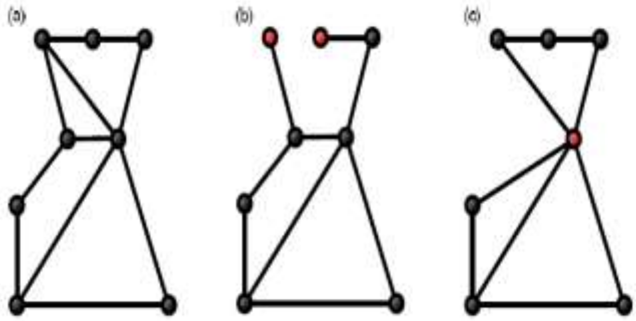


Fig. 3-4: A biconnected network with (a) no nodal degree, nodal degree of one (b), no articulation points or bridge nodes as in (c)

3.2.2 Shortest Path Algorithms

The main objective of the shortest path algorithms is to find the shortest path with least cost. Considering the graphs with non-negative weight edges, Dijkstra algorithm can be used to obtain the minimum path [Di59]. For edges of negative weight, Ford-Fulkerson shortest path algorithm or Bhandari – modified Dijkstra algorithm can be used. Dijsktra's algorithm is useful because of the concept of labeling and scanning technique, so that this basic algorithm can be easily modified to a variety of other search purposes. Dijkstra's algorithm relies on building a tree with minimum cost from source to the corresponding nodes, in order to find the minimum path.

The key concept of the Dijkstra's algorithm is based on label and scanning. The node with a minimum distance from the source node so far is labeled without any memory of the route followed, but a tag referring to the previous node that has reached this node with minimum distance. Labeling is done with a tag that has two attributes: tag = {distance} predecessor. In this context, predecessor is the neighboring node. Labels are initialized temporarily to a possible path that passes through the respective node. When the shortest path between two nodes is chosen, these labels become permanent, which means that it will not change. Scanning is the process of looking from one node to the other adjacent nodes, which are not permanently labeled. Their labels are updated temporarily with the new predecessor and distance information, if the new distance is less. Otherwise, the predecessor and distance information remain the same.

3.2.2.1 **Dijkstra Algorithm**

The basic procedure for finding the shortest path from a source node s to a destination node t is given in Fig. 3-5, in the form of a pseudocode:

```
Procedure Dijkstra (s)
begin
  S : = {s} ; T = N – {s};
  d(s) : = 0 and pred(s) : = 0; d(j) = ∞ for each j ≠ 1;
  update(s);
  while S ≠ N do (node selection, also called
FINDMIN)
       let i ∈T be a node for which d(i) = min {d(j) : j ∈
       T};
       S : = S ∪ {i}; T: = T – {i};
       update(i)
end;

Procedure Update (i)
 for each (i,j) ∈ A(i) do
       if d(j) > d(i) + cij then
              d(j) : = d(i) + cij
              pred(j) : = i;
```

Fig. 3-5: Pseudocode of Dijkstra's algorithm

The scanning procedure and labeling procedures are given in the form of a pseudocode, as a method of Update, where c_{ij} is the distance of the edge between the nodes i and j and $d(i)$ is the total distance of the label of the node i. Labeling is done by checking the Update(i) and node with lowest cost is kept and the predecessor is assigned with the information of this node. This procedure continues until all the nodes are checked and [T] becomes empty.

When the algorithm is completed, the vectors (or ordered sets) [S] and [T] build a tree of shortest path, the source node being the root and all other nodes included being end nodes of the tree. This information and the associated distance can be read from the shortest route of the path. For example, considering the Fig.3-6 Dijkstra solution is used and the shortest way from A to H having a distance of 14, following the path {A-B-C-G-H} can be observed in Fig. 3-7.

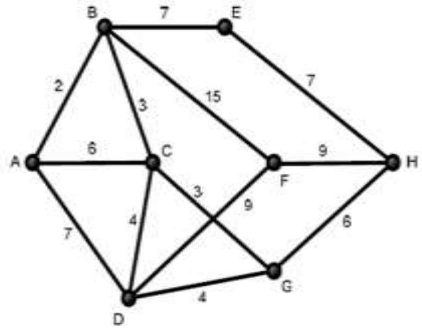


Fig. 3-6: Graph example for the Dijkstra algorithm

Table 2-1

step	node	perm. label
0	A	(source)
1	B	{2, from A}
2	C	{5, from B}
3	D	{7, from A}
4	G	{8, from C}
5	H	{14, from G}
6	E	{9, from B}
	F	{16, from D}

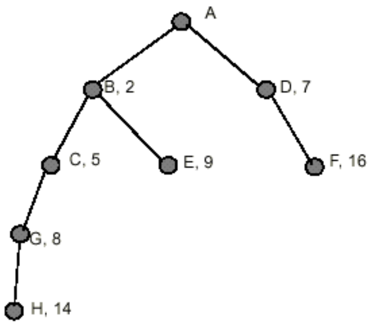


Fig. 3-7: Solution of the Dijkstra algorithm

Due to the fact that the algorithm can be completed by obtaining the shortest path in the tree, each node has to be visited as a recent node for a given request and permanently labeled after visiting. As the scanning process could include n-1 other nodes in the worst case, the time complexity of Dijkstra's algorithm is O(n2) where n is the number of nodes. However, through various data structures operating for each iteration, it is possible to reduce the time complexity of the performance of the algorithm to O(n log n) [MaGr94] or O (log n S) where S is the number of the edges in the graph.

3.2.2.2 **K-shortest path algorithm**

K-shortest path algorithms extend the shortest path algorithms, aiming to have k number of shortest paths, starting from the shortest path and the rest (k-1) are ordered by increased costs. The purpose of the algorithm is that in some cases, it might be necessary to have more than one shortest path between two nodes of a network. There are two types of KSP algorithms:

1. Paths are not required to be loopless and paths are allowed to be revisited on the same node for more than once. For this case, David Eppstein's algorithm reaches the best running time complexity [Ep98].
2. The paths are required to be loopless. For this case, Yen's algorithm is used, where only simple paths are considered.

In this work, Yen's algorithm is used, since the paths are loopless. The pseudo code of the Yen's algorithm for k-shortest paths is given in Fig. 3-8:

```
function YenKSP(Graph, source, sink, K):
   // Determine the shortest path from the source to the sink.
   A[0] = Dijkstra(Graph, source, sink);
   // Initialize the heap to store the potential kth shortest path.
   B = [];

   for k from 1 to K:
       // The spur node ranges from the first node to the next to last node in the shortest path.
       for i from 0 to size(A[k - 1]) - 1:

           // Spur node is retrieved from the previous k-shortest path, k - 1.
           spurNode = A[k-1].node(i);
           // The sequence of nodes from the source to the spur node of the previous k-shortest path.
           rootPath = A[k-1].nodes(0, i);

           for each path p in A:
               if rootPath == p.nodes(0, i):
                   // Remove the links that are part of the previous shortest paths which share the same root path.
                   remove p.edge(i, i + 1) from Graph;

           // Calculate the spur path from the spur node to the sink.
           spurPath = Dijkstra(Graph, spurNode, sink);

           // Entire path is made up of the root path and spur path.
           totalPath = rootPath + spurPath;
           // Add the potential k-shortest path to the heap.
           B.append(totalPath);

           // Add back the edges that were removed from the graph.
           restore edges to Graph;

       // Sort the potential k-shortest paths by cost.
       B.sort();
       // Add the lowest cost path becomes the k-shortest path.
       A[k] = B[0];

   return A;
```

Fig. 3-8: Pseudocode of Yen's algorithm

First of all, it has to be indicated that this algorithm uses Dijsktra algorithm in order to find the shortest path between two nodes. However, to determine the shortest path from the source node to the destination node in the network, any shortest path algorithm can be used. Nonetheless, Dijkstra's algorithm is preferred in this work.

The algorithm aims to hold two containers of paths, A and B, former is for the k-shortest path and the latter is for the potential k-shortest paths. First of all, the shortest path is obtained by using Dijkstra algorithm, it is added to the container A. Secondly, the source node becomes the spur node and the edge between the spur node and the intermediate node used in the initial shortest path is removed. After the removal of this edge, the second shortest is obtained and added to the container B. The same procedure continues until K-1 number of shortest paths are obtained and added to the container B. Then, the shortest paths in container B are ordered by incrementing values of total cost and moved to the container A. Finally, the container A consists of the K-shortest paths.

3.2.3 Path computation

3.2.3.1 Routing and Wavelength Assignment (RWA)

In WSON, a RWA algorithm provides optical connections finding a physical route and assigning a wavelength to the connection request [Za00]. The RWA has a crucial importance to increase the efficiency of the optical networks that are wavelength-routed. A good solution of the RWA problem assigns more customers that are demanding connection and less customers are to be rejected in case of congestion [Oz03].

The main objective of the RWA algorithms is to allocate a route and a particular wavelength to each connection request and therefore, to maximize the number of connections that are set up. The wavelength must be persistent through the entire path, except that wavelength converters are utilized. Note that when no wavelength converters are available in the network, the wavelength continuity constraint (WCC) must be ensured assigning a wavelength that must be currently unused in every link in the route.

Principally there are two general approaches to solve the problem regarding the complexity of RWA. The first methodology proposes to solve the routing problem in the first place and then to accomplish the wavelength assignment. The second methodology is to manage route selection and wavelength assignment simultaneously.. Moreover, in a wavelength-routed WDM network, the wavelength-continuity constraint might be discarded if a wavelength converter can be used, in order to convert the wavelength of the received data into another wavelength at an intermediate node, before transmitting it on the next link. This method is known as wavelength conversion and the wavelength-routed networks that are able to perform wavelength conversion are known as wavelength-convertible networks. Besides, a single lightpath in a wavelength-convertible network can utilize a different wavelength through each link of the path. Therefore, the efficiency in the network may be increased by solving the wavelength issues of the lightpaths with the deployment of wavelength conversion [Za00].

3.2.3.2 Routing and Spectrum Assignment (RSA)

In flexgrid optical networks, the similar problem as in RWA is called the Routing and Spectrum Allocation (RSA) since it finds a physical route and allocates a set of slots to connection requests. However, besides the spectrum continuity constraint similar to WCC in RWA, the RSA problem adds the spectrum contiguity constraint, i.e. the frequency slots allocated for a connection request must be contiguous in the spectrum along the links in its route. RSA algorithms are used either in the network planning phase when the set of connection requests is known in advance (offline RSA algorithms) [Ch11], [Wa11.2], [Kl11], [Ve12.3], or to dynamically provision connections at arrivals of requests (dynamic RSA algorithms) [Wa11.1].

As difficulty of the RSA problem lays in the fact that, apart from the spectrum continuity constraint in each link along the routing path, the spectrum contiguity constraint must be also ensured, some works in the literature propose to use a dedicated graph for each of the wavelengths available in the WDM grid, in order to solve the RWA+WCC problem. An algorithm using parallel graphs can be adapted to solve the RSA problem by defining channels, i.e. sets of spectrum contiguous frequency slots; a dedicated graph must be used for each channel. Channels were introduced in [Ve12.3] as a concept to simplify the offline RSA problem. The use of connection request-tailored channels allows removing the spectrum contiguity problem from mathematical formulations. Channels can be grouped as a function of the number of slots, e.g., the set of channels C2 = {{1,1,0,0,0,0,0,0}, {0,1,1,0,0,0,0,0}, {0,0,1,1,0,0,0,0}, … {0,0,0,0,0,0,1,1}} includes every channel using 2 contiguous slots, where each position is 1 if a given channel uses that slot. The size of the complete set of channels C that need to be defined is bounded by $|S| \cdot n$, where S represents the set of FSs and n is the number of different amounts of contiguous slots that connections can request, e.g. if connections can request for either 1, or 2, or 4, or 16 contiguous slots, n=4. Then, the number of parallel graphs that need to be maintained and the number of times the shortest path algorithm is run can be as large as 3200 in a 5 THz spectrum using 6.25 GHz slots.

3.3 Conclusions

In this chapter, graph theory and related network terminologies were firstly introduced. Secondly, shortest path algorithms such as Dijkstra's algorithm and Yen's k-shortest path algorithm were explained, in order to provide fundamental background for further chapter of this work. Finally, path computation problems and relevant algorithms were pointed out.

Chapter 4

PCE Architecture

The Path Computation Element (PCE) is an architecture supported by IETF that suggests a dedicated network item assigned to path computation process. The PCE beatens the visibility and distributed provisioning inefficiency problems. In scope of the PCE architecture, the techniques proposed by the IETF are based on path computation performed by assigned network items (i.e., the PCEs). Therefore, it is important to comprehend the principal structure of the PCEs. The PCE performs path computation for the network nodes after collecting link-state information. It may also be utilized by other information resources, e.g. network management system (NMS), to obtain detailed information about resource allocation (e.g. used wavelengths) or physical network parameters (e.g. link length, impairments). Moreover, the PCE is also beneficial to the network nodes to prevent from high CPU-intensive path computations and to provide effective TE solutions in case of legacy network nodes.

The interaction between path computation clients (PCC) and PCEs is realized via the PCE protocol (PCEP), which also provides inter-PCE communications providing an efficient way to accomplish TE-based path computation between cooperating PCEs in multi-layer/domain cases and meanwhile maintaining scalability and confidentiality [Pa13]. The PCE is responsible of the path computation in its own layer/domain, where it has full visibility and updated information on available network resources. In multilayer/domain scenarios, there is a co-operation between PCEs by sharing the result of each (intra-domain) path computation. Thus, the entire source-destination path consists of the combination of each solution provided by each PCE and no additional information is exchanged between different domains.

This chapter provides the main mechanisms of the PCE architecture in the context of core network's control plane and the principles of the PCEP operations.

4.1 Functional Blocks of PCE Architecture

The PCE architecture is based on two functional elements: the PCE and the PCC. The PCE is operated on a dedicated server, which performs constraint-based path computation demanded by PCC's. The PCC is usually deployed on a NMS or a network node (e.g., the demanded LSP source node). A PCE might also operate as PCC demanding path computations to other (peer or hierarchically higher) PCEs. PCC and PCE interact through PCEP. Fig. 4-1 presents the conventional PCE internal architecture. The fundamental component modules are the Traffic Engineering Database (TED), the path computation module and the communication module. The TED collects information about network topology and the actual TE information (e.g. link bandwidth utilization) produced by routing protocols session (e.g., OSPF-TE) or other mechanisms (e.g., by the NMS). Based on selected algorithms and particular policies, the path computation module computes the requested paths. The communication module has a role of being an interface to manage communication protocols (e.g., routing protocols and PCEP). The PCE can be set up within a network node (i.e., internal PCE) or a dedicated physical device (i.e., external PCE).

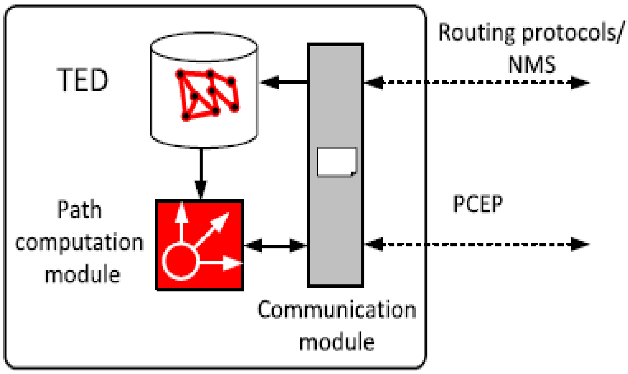


Fig. 4-1: Functional modules of a Path Computation Element

Either a single PCE or multiple PCEs perform the computation of an LSP. In the former case, presented in Fig. 4-2-a, the PCE provides the detailed end-to-end path route (step 1-2, dotted lines), while in the latter case, presented in Fig.4-2-b and Fig.4-2-c, more than one PCEs take place in performing the path computation, either in independent, peer or hierarchical fashion. Exclusively, in multiple PCE computation, each PCE performs a path segment computation (e.g., in Fig.4-2-b PCE1 computes A-B-C at step 1-2, PCE2 computes C-D at step 5-6), in multiple inter-PCE computation, en-to-end path is the result of cooperative computation between PCEs (e.g., in Fig.4-2-c upon request reception at step1, PCE1 forwards the request to PCE2 -step 2- which performs C-D segment at step 3, then PCE1 performs the segment at step 3, then PCE1 computes the segment A-BC, join the two segments together and provides the end-to-end path to source node at step 4).

The temporal bond between path computation and signaling relies on the considered network scenario and the preferred PCE architecture. In the case of a single PCE, initially the source node (acting as PCC) requests end-to-end path computation to PCE, then it activates signaling protocol in order to allocate resources along the computed path. The process is presented in Fig.4-2-a. In the case of multiple PCEs, there exist two different actions to be performed:

1. signaling is activated upon each segment path computation (see Fig.4-2-b).
2. signaling is activated upon end-to-end inter-PCE path computation (see Fig.4-2-c).

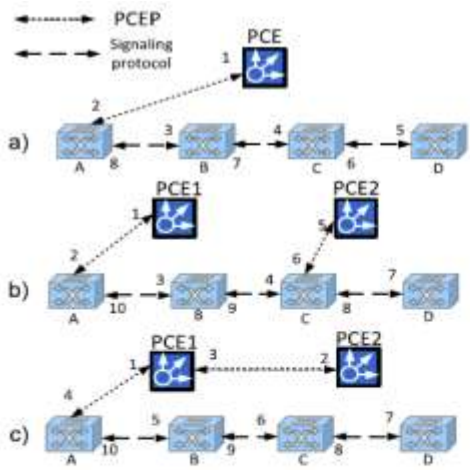


Fig. 4-2: Single PCE computation (a), multiple PCE computation (b), multiple inter-PCE computation

It is necessary for a general PCE architecture that each PCC has the information of the presence and location of a PCE in the controlled domain and the definition of its path computation area. PCE discovery methodologies involve automatic and dynamic detection of PCEs including additional information about provided capabilities and target area/domain, in order to accomplish the most appropriate PCE selection for a given path computation request. The PCE computes a path based on its internal Traffic Engineering Database (TED) that includes the network topology and the actual TEs information (e.g., link bandwidth utilization). Assuming the considered network scenario, a PCE executes path computation on a particular area. Therefore, the PCE - TED visibility is limited to a single area, domain or layer and the PCE executes path computation demands having, as source, a node belonging to the TED. Thus, a single path computation request is adequate in most cases to provision intra-area/domain/layer LSP, whereas path computation of LSPs crossing over more areas/domains/layers need coordination between each PCE that is associated. The tree represented in Fig. 4-3 summarizes the main functionalities in the PCE architecture.

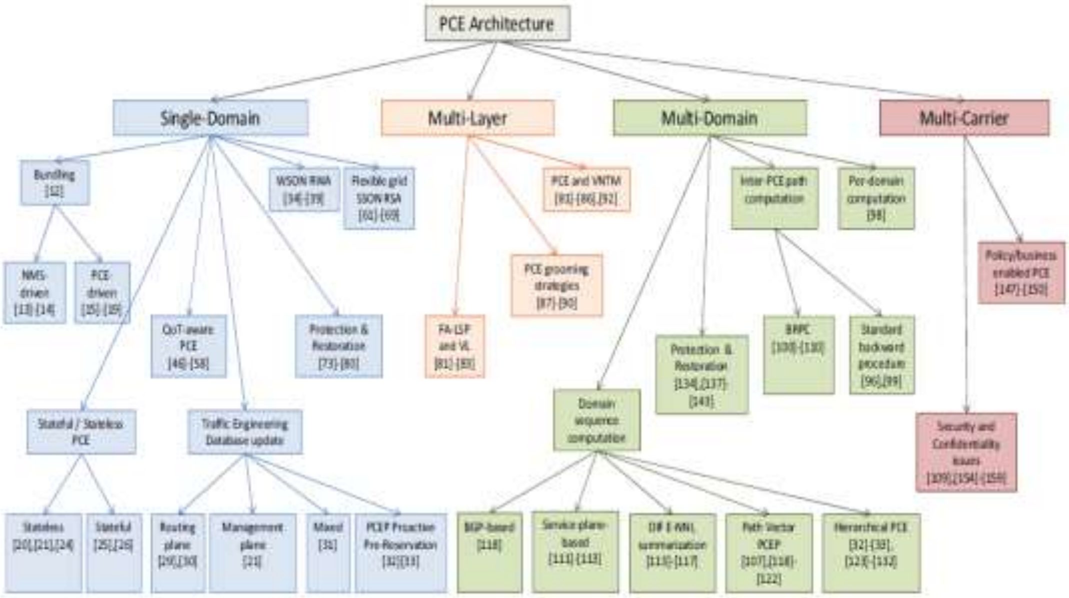


Fig. 4-3: The PCE architecture scheme

4.2 PCE Communication Protocol (PCEP) Server

The main protocol scheme of PCEP consists of a client-server intercommunication among PCC and PCE. The PCC can be a network node (e.g., ingress node), a network operator, the NMS, or another PCE. Interaction is performed through the exchange of PCEP messages traversing over TCP/IP, to impose on its reliability, Messages are designated to start, maintain and terminate a PCEP session. Initially, PCC and PCE introduce a PCEP session within a TCP session, in order to accomplish path computations. The exchange of Open and Keepalive messages are involved in PCEP session establishment, in order to agree on session parameters, such as timers and session refresh messages. The core of the protocol interaction is performed with the exchange of two PCEP messages: the Path Computation Request (PCReq) message and the path Computation Reply (PCRep) message. Further messages are also designated to manage particular events and communication errors (e.g., Error (PCErr) and Notification (PCNtf) messages). The PCEP session ends upon the reception of a Close message.

As a path computation request is involved in a PCReq message indicating all the demanded parameters and constraints, the PCReq message requires two necessary objects:

- End-Points Object: includes the IP addresses of the source and destination of the required path, which may correspond to the end nodes of the whole path (i.e., LSP) or of a path segment.

- Requested Parameter Object (RP): covers the request-ID utilized to particularly identify each path computation request activated by a PCC. Flags are defined to demand computation priority, re-optimization of a previously set path, bidirectional path computation (with the same TE parameters in both directions) and whether the routes are expected to be strict or not. In strict routes, the list of nodes to be crossed is precisely specified (i.e., strict nodes) whereas in loose routes it is indicated by a partial sequence or abstract nodes.

Additional objects may also be covered by the PCReq message, in order to perform different tasks and indicate different constraints. Regarding the Path Computation Reply message, the PCE returns a PCRep message, containing only one necessary object, the RP Object, if no errors are present. The RP Object supplies the request-ID of the computed request. If a path computation failure is present, caused by unsatisfied set of constraints, the PCRep contains a NO-PATH Object, possibly extended by additional information about the failure reasons. For instance, if the path could not be set because of inadequate bandwidth, the Bandwidth Object is attached to inform the PCC. If the PCE computes the required path successfully, the PCRep contains an Explicit Route Object (ERO). The ERO may include a list of strict and/or loose nodes (containing IPv4/IPv6 addresses, Autonomous Systems (AS) numbers as abstract nodes) to be utilized by the signaling protocol to set the LSP. Furthermore, the Metric Object may be present, in order to display the metric cost of the computed path [Pa13].

4.3 Conclusions

In this chapter, PCE architecture was introduced, which is necessary for path computation. In order to have a deeper understanding, functional blocks of this architecture were mentioned and PCEP protocol, taking part between PCE and PCC, was explained.

Chapter 5

Lightpath computation in translucent networks

During the propagation of optical signals, QoT is exposed to degradation caused by physical layer impairments, which leads to undesirable BER at the receiver. Therefore, the 3R regenerators are placed at the intermediate nodes, in order to be utilized when the optical signal need to be electronically regenerated before it reaches the receiver. Whereas the regenerators are expensive resources, the usage of them requires optimization. The path computation is performed by a centralized PCE, which finds routes that meet the required OSNR threshold for each incoming requests of connection.

The reachability is a main constraint in translucent networks and the modulation format used in transmission has a significant effect on reachability. For instance,

Fig. 5-1 is an example to demonstrate the effect of reachability. Let's assume that the maximum reachable distance of 16 QAM modulation format for 100 Gb/s is 1000 km and of QPSK for 400 Gb/s is 3000 km. In order to provide a desirable BER at the receiver, using only QPSK modulation, node C should be utilized as a regenerator node and there will be 2 lightpaths from the source to the destination nodes: A – C and C – E. However, if 16-QAM is to be used, regeneration will be required at nodes B and D, due to the fact that 16-QAM cannot transmit further than 1000km. This case, A – B, B – D and D – E will be the lightpaths from the source to the destination node and both modulation formats will be used (16-QAM to be used for the lightpaths A – B and D – E and QPSK to be used for the lightpath B – D). As indicated, different lightpaths can utilize different modulation formats and this is another feature of flexibility to the transmission.

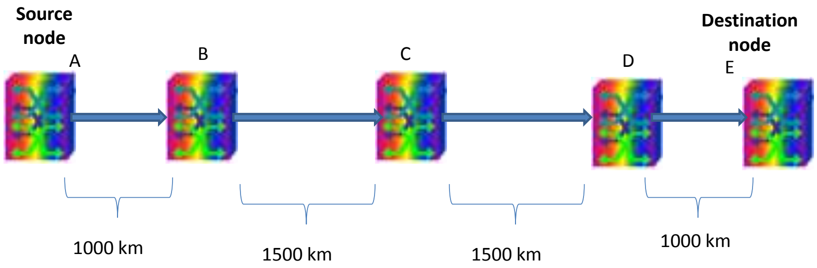


Fig. 5-1: An example for the effect of reachability

5.1 Problem statement

The impairment aware routing and spectrum allocation problem basically considers finding a feasible route and allocating the demanded spectrum for the request of connection minimizing the usage of the regenerators, which are used to guarantee the QoT. As a second objective, the length of the route should also be minimized. This requires selecting the route with minimum number of hops. The implementation of the PCE-based IA-RSA algorithm is performed by experimental evaluation and its performance is interpreted by analyzing the results and comparing with the existing IA-RSA algorithms with/without regenerators.

5.2 Proposed algorithm

Before introducing the algorithm, some notation used in this work has to be mentioned. The network topology and the state of the resources such as availability of the regenerators of every node are known due to the TED containing the information. The network topology is represented with the graph G(N,E), where N is the set of optical nodes, E is the set of optical links. Let $N_R \subseteq$ N be the subset of nodes with regeneration capability and conversely $N_R \subseteq N$ the subset of nodes without regeneration capability. Thus $N = N_R \cup N_T$. Additionally, we are given a pair of source and destination nodes $\{s,t\}$ for the connection being requested.

The algorithm consists of two phases. The first phase, pseudocode representation is given in the Fig. 5-2, brings up a new graph representation, which states the connectivity among particular nodes, for instance, two nodes are connected in this graph representation only for 2 cases:

1) There is a shortest path from the source node to the connected nodes and nodes with regeneration capability,

2) There is a shortest path from a regeneration capable node to the connected nodes and other regeneration capable nodes.

```
Phase 1:
for each (u, v) ∈ N
      D(i) ← add_vertex(i)
           for each (w, y) ∈ N
                     if (u==v) continue
                     elseif  exists(shortestpath(u, v))
                          D(u) ←add_edge(u, v)
                     if (u == v)  continue
                     if(v.hasConvertionCapability())
                         N_Reg ←add_vertex(v);
```

Fig. 5-2: Pseudocode of Phase 1 of the proposed algorithm

Hence, these cases need to be examined in phase one, which constructs a set of digraphs $\mathcal{D}_i$ (N, $\mathcal{A}$), where i indicates the corresponding source node, N represents the set of optical nodes and $\mathcal{A}$ the feasible set of connectivity link between nodes in N. The shortest path between two nodes in $\mathcal{D}_i$ has to satisfy the threshold of OSNR. For the whole shortest path, k number of shortest paths between the source and destination nodes in $\mathcal{D}_i$ have to be acquired, in order to keep alternative shortest paths regarding possible physical impairments. It has to be noted that the aforementioned shortest paths only represent that connection between two nodes can be computed, not that real lightpath is established. For instance, Fig. 5-3a being the graph representation of the network, Fig. 5-3b represents the Digraph for the source node and the links between a pair of nodes corresponds to the connectivity that in the original graph there exists a shortest path between those two nodes.

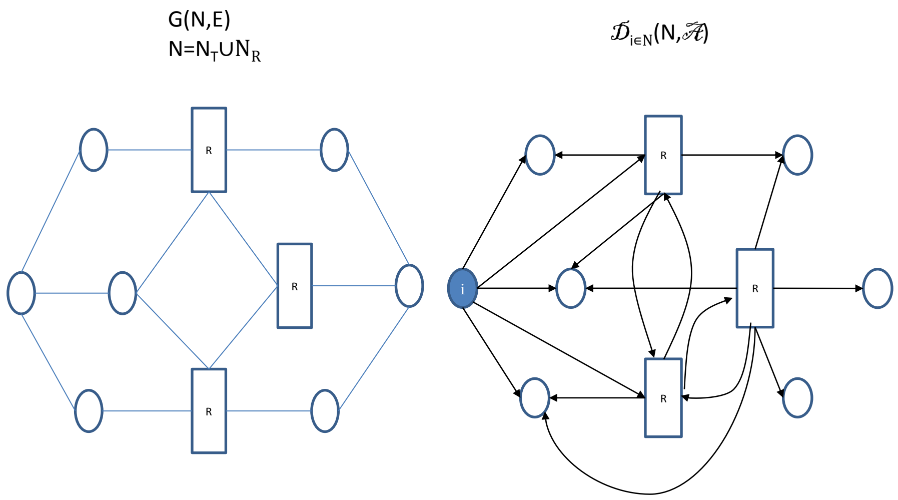


Fig. 5-3: Graph and digraph representations of a given network

The second phase, whose pseudocode is given in Fig. 5-4, is based on the already created digraphs in phase one. First of all, digraphs $\mathcal{D}_i$ have to be updated according to the current states of the links, which should be unavailable if the intermediate nodes with regeneration capability are not available to be used, in case the maximum regeneration capacity is reached. The regeneration capabilities of the nodes are limited and cannot be exceeded. Therefore, this condition has to be checked frequently, in order to update the availability of the regenerators. Secondly, if there is no available route, a notification states that there are no resources. Then, for every single shortest path from digraph $\mathcal{D}_i$, in total of k-shortest paths, RSA is computed and the shortest path is determined for each pair having a link in between. The Dijkstra's shortest path algorithm is preferred here and each solution returns a lightpath with minimum number of hops, satisfying the required OSNR and bandwidth conditions. Finally, the feasible k-shortest path solutions with minimum number of regenerators and minimum hops are obtained.

```
Phase 2:
for each n ∈ N_Reg
    update_regenerators(D(i))
    k_paths ← compute_kshortestpaths(S, D, K)
    if k_paths = Ø
    return NO_RESOURCES
for each k ∈K
    for each (u, v) ∈ D(i)
        k_paths_ordered ←order_kshortestpaths(k_paths, S, D, BW)
        best_path = min_hop(k_paths)
        return best_path
```

Fig. 5-4: Pseudocode of Phase 2 of the proposed algorithm

5.3 Conclusions

In this chapter, the main issues of the path computation are examined. The two main constraints to be satisfied, minimizing the number of regenerators and obtaining the shortest path with minimum hops, are aimed to be altered with the proposed algorithm. The algorithm introduced two phases, the first phase proposes the concept of creating an auxiliary graph, which aims to minimize the number of regenerators and the second phase determines the k-shortest paths, which satisfy the OSNR condition.

Chapter 6

Evaluation of the results

6.1 Network environment

The experimental assessment of the proposed algorithm was conducted on a specialized simulator developed in Omnet++ 4.3. The IA-RSA algorithm was implemented in C++ and utilized by a dedicated centralized PCE as a callable algorithm, which manages the connection requests dynamically.

The performance of the proposed algorithm was evaluated on the 22 nodes and 34 links European Optical Network (EON) depicted in Fig. 6-1. Each node was equipped with 1 to 5 regenerators and its OSNR had been fixed to 41dB. Both length and OSNR of each link are also shown in Fig. 6-1. The spectrum width was fixed to 1THz and the slot width to 6.25GHz.

A dynamic network environment is simulated for the network under study, where incoming connection requests arrived following a Poisson process and were sequentially served without prior knowledge of future incoming connection requests. The holding time of connections was exponentially distributed with the mean value equal to 2 hours. Source/destination pairs are randomly chosen with equal probability (uniform distribution) among all network nodes. Different values of offered network load were considered by changing the arrival rate while keeping the mean holding time constant. The bit rate demanded by each connection request was 1Gb/s. For all the tests the OSNR threshold was fixed to 19dB. Each test consisted on 15000 independent connection requests, and everyone was repeated 10 times with a different seed.

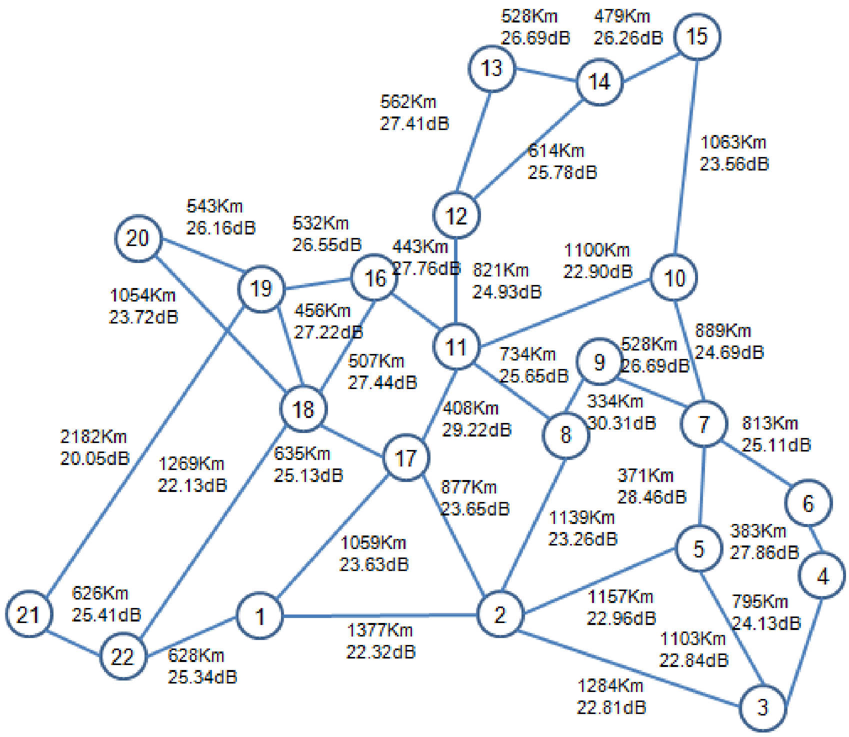


Fig. 6-1: 22-node and 34-link EON topology

6.2 Performance evaluation

Fig. 6-2 plots the blocking probability as a function of the offered traffic load to the network expressed in Erlangs (mean holding time / mean inter-arrival time).

As illustrated, as soon as the amount of regenerators per node is increased, the amount of traffic served for a given Pb_{bw} notably increases. This is a consequence of the fact that more connections can be allocated fulfilling the signal quality constraint. It is clear that if more regenerators are added to network, more lightpaths, which could have been blocked because of low OSNR, can be provisioned, and thus, more traffic can be conveyed. Notice that, also adding regenerators alleviates to some extent the spectrum continuity constraint, allowing a more optimize spectrum resources exploitation.

It is worth highlighting, that when the signal quality constraint was relaxed (i.e., not taken into account), almost 50% of provisioned lightpaths had a total OSNR *lower* than 19dB. This means that half of the served lightpaths were unusable because of high signal noise, which also implies a deficient use of resources (resources allocated to bad quality ligthpaths).

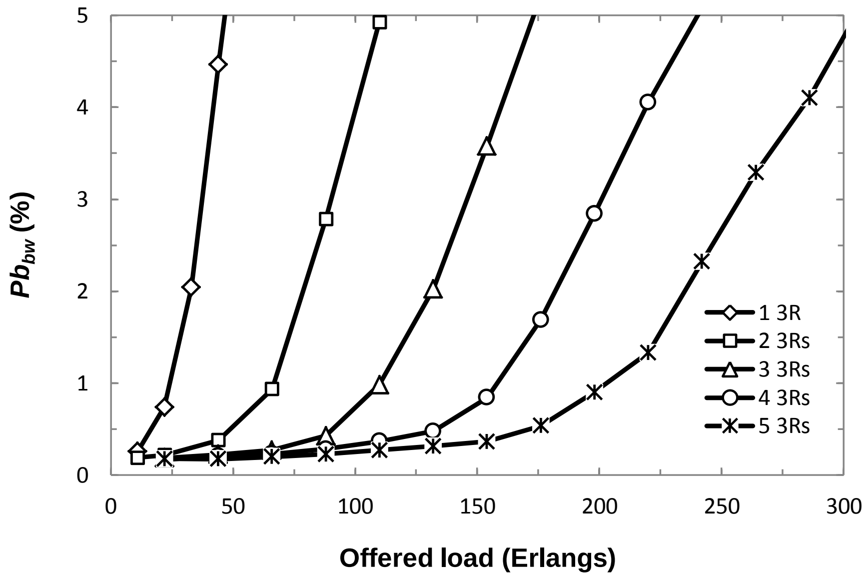


Fig. 6-2: Blocking probability vs. offered load

Table 6-1 Gain of using different regenerators amount configuration

	1 3R	2 3Rs	3 3Rs	4 3Rs
2 3Rs	275.87%			
3 3Rs	456.01%	165.30%		
4 3Rs	653.28%	236.81%	143.26%	
5 3Rs	839.02%	304.14%	183.99%	128.43%

Table 6-1 summarizes the gains of using different amount of regenerator per node, ranging from 1 to 5. Presented values are for Pb_{bw}=1%. It is shown, that adding one extra regenerator entails a minimum gain of 128.43% of traffic; when comparing using 5 regenerators against using 4. Moreover, a maximum increase of 839% is attained when adding 4 extra regenerators. In addition, just upgrading from a configuration of 1 regenerator per node to 2 per node, implies an improvement of 275.87%; endorsing the optimized use of regenerators done by the devise algorithm.

Chapter 7

Conclusions

A novel impairment aware RSA in translucent Flexgrid Networks has been devised. It aims at first minimizing the number of regenerators, and second the number of hops when calculating a new lightpath. For this propose the algorithm uses auxiliary digraphs, and a two phase computing steps.

The numerical results were obtained through an ad hoc implemented simulator, in Omnet++, in terms of blocking probability. This allows an exhaustive study of the IA-RSA algorithm performance (including different number of regenerators availability). Results showed that when using the IA-RSA algorithm more traffic load can be offered to the network. Additionally, a gain in terms of traffic bitrate conveyed as low as 128%, and as high as 839% can be observed between the different scenarios tested with different amount of regenerators per node.

List of Acronyms

ASE	Amplifier Spontaneous Emission
ASON	Automatically Switched Optical Network
BER	Bit Error Rate
BV-OXC	Bandwidth-Variable Optical Cross Connect
BV-T	Bandwidth-Variable Transponder
BV-WSS	Bandwidth-Variable Wavelength Selective Switch
CCAMP	Common Control and Measurement Plane
CD	Chromatic Dispersion
CP	Connection Point
CWDM	Coarse Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
FCAPS	Failure Management, Configuration Management, Accounting, Performance, Security
FS	Frequency Slot
GMPLS	Generalized Multiprotocol Label Switching
GoS	Grade of Service
GVD	Group Velocity Dispersion
IA-RSA	Impairments-aware Routing and Spectrum Allocation
IETF	Internet Engineering Task Force
LMP	Link Management Protocol

LSP	Label-Switched Path
MPLS	Multi Protocol Label Switching
OADM	Optical Add/Drop Multiplexer
OCC	Optical Node Connection Controller
OEO	Optical-Electronic-Optical
OFDM	Orthogonal Frewuency Division Multiplexing
OSPF-TE	Open Shortest Path First – Traffic Engineering
OTN	Optical Transport Network
OXC	Optical Cross Connect
PCE	Path Computation Element
PCEP	PCE Communication Protocol
PMD	Polarization Mode Dispersion
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QoT	Quality of Transmission
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RSA	Routing and Spectrum Allocation
RSVP-TE	Resource Reservation Protocol – Traffic Engineering
RWA	Routing and Wavelength Assignment
SNC	Sub-Network Connection
SPM	Self Phase Modulation
TCP	Termination Connection Point
TE	Traffic Engineering
TED	Traffic Engineering Database
WCC	Wavelength Continuity Constraint
WDM	Wavelength Division Multiplexing

WSON	Wavelength-Switched Optical Networks
WSS	Wavelength Selective Switch
XPM	Cross-phase Modulation

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