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Optical Network Planning for Static Applications

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Resumo

Os pedidos de tráfego nas redes de transporte ópticas continuam a crescer, tanto em número como em tamanho, a um ritmo incrível. Consequentemente, a utilização eficiente dos recursos das redes nunca foi tão importante como hoje. Uma solução possível para este problema passa por planear, desenvolver e implementar algoritmos eficientes para aplicações estáticas e/ou dinâmicas de modo a minimizar a probabilidade de bloqueio e/ou minimizar o número de comprimentos de onda. Os algoritmos de encaminhamento e de atribuição de comprimentos de onda (RWA) estáticos utilizam um determinado conjunto de pedidos de caminhos ópticos e visam fornecer um plano de longo prazo para tráfego futuro. Os algoritmos RWA estáticos são importantes para as redes em multiplexagem por divisão de comprimento de onda (WDM) atuais e futuras, especialmente quando não há conversão de comprimento de onda, a rede é altamente ligada ou a carga de tráfego é de moderada a alta.

Nesta dissertação, propomos desenvolver uma ferramenta de planeamento de redes ópticas capaz de escolher o melhor caminho óptico e atribuir o mínimo de comprimentos ondas possíveis. Esta ferramenta está estruturada em cinco fases: numa primeira fase é definida a topologia física de rede pela matriz das adjacências ou pela matriz de custo e a topologia lógica é definida pela matriz de tráfego; numa segunda fase é utilizado o algoritmo Dijkstra para encontrar o caminho mais curto para cada ligação; na terceira fase o encaminhamento de tráfego é realizado considerando uma unidade de tráfego entre os nós de origem e destino; na quarta fase os caminhos são ordenados tendo em conta as várias estratégias de ordenação, tais como Shortest Path First, Longest Path First e Random Path Order; finalmente, na quinta fase, os algoritmos heurísticos são utilizados para atribuição de comprimentos de onda, como Graph Coloring, First-Fit e Most-Used. Esta ferramenta é primeiramente testada em redes pequenas (por exemplo, topologias em anel e em malha), e depois é aplicada a redes reais (por exemplo, redes COST 239, NSFNET e UBN). Concluímos que o número de comprimentos de onda calculados para cada rede é quase independente da heurística para atribuição dos cumprimentos de onda, bem como da estratégia de ordenação dos caminhos, quando uma topologia lógica em malha completa é considerada.

Palavras-Chave

Algoritmos heurísticos, aplicações estáticas, redes ópticas, ROADM, RWA, WDM.

Abstract

Traffic demands on optical transport networks continue to grow, both in numbers and in size, at an incredible rate. Consequently, the efficient use of network resources has never been as important as today. A possible solution to this problem is to plan, develop and implement efficient algorithms for static and/or dynamic applications in order to minimize the probability of blocking and/or minimizing the number of wavelengths. Static Routing and Wavelength Assignment (RWA) algorithms use a given set of optical path requests and are intended to provide a long-term plan for future traffic. Static RWA algorithms are important for current and future WDM (Wavelength-Division Multiplexing) networks, especially when there is no wavelength conversion, the network is highly connected or the traffic load is moderate to high.

In this dissertation, we propose to develop an optical network planning tool capable of choosing the best optical path and assigning as few wavelengths as possible. This tool is structured in five phases: in the first phase, the network physical topology is defined by the adjacency matrix or by the cost matrix and the logical topology is defined by the traffic matrix; in a second phase, the Dijkstra algorithm is used to find the shortest path for each connection; in the third phase, the traffic routing is accomplished considering one traffic unit between the source and destination nodes; in the fourth phase, the paths are ordered using various ordering strategies, such as Shortest Path First, Longest Path First and Random Path Order; finally, in the fifth phase, the heuristic algorithms for wavelength assignment, such as Graph Coloring, First-Fit and Most-Used are used. This tool is first tested on small networks (*e.g.* ring and mesh topologies), and then applied to real networks (*e.g.* COST 239, NSFNET and UBN topologies). We have concluded that the number of wavelengths calculated for each network is almost independent of the Wavelength Assignment (WA) heuristics, as well as the ordering strategy, when a full mesh logical topology is considered.

Keywords

Heuristic algorithms, optical networks, ROADM, RWA, static applications, WDM.

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Abbreviations

AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
DEMUX/MUX	Demultiplexer/Multiplexer
EDFA	Erbium Doped Fiber Amplifier
FEC	Forward Error Correction
IP	Internet Protocol
ITU	International Telecommunications Union
LCoS	Liquid Crystal on Silicon
MEMS	Micro Electro Mechanical System
MPLS	Multi-Protocol Label Switching
OA	Optical Amplifier
OADM	Optical Add/Drop Multiplexer
ODU	Optical Channel Data Unit
OMS	Optical Multiplex Section
OPU	Optical Channel Payload Unit
OSNR	Optical Signal-To-Noise Ratio
OTM	Optical Transport Module
OTN	Optical Transport Networks
OTS	Optical Transport Section
OTU	Optical Transport Unit
PON	Passive Optical Network
RLF	Recursive Largest First
ROADM	Reconfigurable Optical Add Drop Multiplexer
RWA	Routing and Wavelength Assignment
SC	Single Channel
SONET/SDH	Synchronous Digital Hierarchy/Synchronous Optical Network
WA	Wavelength Assignment
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch

Chapter 1 – Introduction

1.1. Motivation

The history of optical networks has started in the late eighties of last century, with the development of optical amplification and Wavelength Division Multiplexing (WDM).

Both of these technologies allowed to take much more advantage of the huge transport capacity of optical fiber. In these first networks, optical technology was only used for transmission since the network nodes operate in the electrical domain. These networks are called opaque networks. Later on, with the development of optical switching technologies, such as Micro-Electro-Mechanical System (MEMS), and multiplexing/demultiplexing technologies, such as Arrayed-Waveguide Grating (AWG), an optical node could be build, *e.g.* ROADMs. These networks where both the transmission and the nodes operate in the optical domain are called transparent networks, since the signal is routed and transmitted through the network based only on the wavelength, which means that the nodes route this signal independently of his bit rate, modulation format or protocol. So, in a transparent network each optical signal follows a path in the optical network, that must be chosen and have a certain wavelength that must be also chosen [1].

Much research has been done in the area of routing and wavelength assignment (RWA) in the last decades, for both static and dynamic traffic. In this dissertation we will focus on the RWA heuristics algorithms for static traffic, in particular we will study the Graph Coloring algorithm for WA and compare its performance with some common WA algorithms, like the First-Fit and the Most-Used algorithm [2].

With static traffic, the entire set of connections is known in advance, and the problem is to configure lightpaths for these connections in a global way, minimizing network resources, such as the number of wavelengths or the number of fibers in the network.

1.2. Objectives

The main goal of this dissertation is to study and analyze RWA heuristics algorithms for static applications, where the lightpaths do not change over time. Static RWA algorithms are important for current and future WDM networks, especially when there is no wavelength conversion, the network is highly connected or the traffic load is moderate to high.

Examples of applications where static routes are desirable are data replication, application data synchronization and virtual machine migration, all of these are inter-datacenter services [3].

In particular, we will focus our attention on the application of the Graph Coloring problem in optical networks for WA. We will compare its performance with other well known algorithms such as the First-Fit and Most-Used, using the COST 239, NSFNET and UBN networks. We will also study the RWA problem for these networks with and without protection.

1.3. Dissertation Organization

The dissertation is organized as follows.

In Chapter 1, the motivation of this study is highlighted, the main objectives of this dissertation are identified and its structure and main contributions are presented.

Chapter 2 provides some fundamental concepts in optical networks. The concepts of adjacency matrix, cost matrix and traffic matrix are presented. The optical network architecture and respective layers (electrical and optical layers) are briefly discussed. In this chapter we will also describe ROADM evolution, his main components and some of the most used architectures, the Broadcast-and-Select and the Route-and-Select architecture.

In Chapter 3, the RWA planning tool is presented. We will define the 5 sub-problems that compose the RWA problem. Then the routing algorithms are explained, in particular the Dijkstra algorithm. Three ordering strategies for organizing the paths are analyzed, the Shortest Path First (SPF), the Longest Path First (LPF) and the Random Path Order (RP) strategy. For WA we will analyze the Graph Coloring, First-Fit and Most-Used. In order to check the correctness of the code implemented in MATLAB for these algorithms we will use a small ring and mesh networks to test our RWA tool. Furthermore, a scenario with protection (1 + 1 dedicated protection) is also implemented and tested.

In Chapter 4, the RWA tool developed in chapter 3 is used in real networks such as the COST 239, NSFNET and UBN. For these simulations we have considered a full mesh logical topology with one unit traffic.

Finally, Chapter 5 draws the main conclusions of this dissertation as well as possible directions for future work in this area.

1.4. Main Contributions

The main contributions of this dissertation are:

- Implementation of the WA Graph Coloring algorithm with a Greedy Strategy.
- Performance comparison, in terms of the number of wavelengths used, between the Graph Coloring WA, First-Fit and Most-Used for the COST 239, NSFNET and UBN networks, considering a full mesh logical topology, with and without protection.

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Chapter 2 – Fundamental Concepts in Optical Networking

2.1. Introduction

In this chapter we will focus on the basic concepts in optical networking. We will start, in Section 2.2, by introducing the concept of physical and logical topologies and their relation with the graph theory, an important tool in network analysis. We will explain the meaning of the adjacency matrix and traffic matrix. The main topologies types will also be presented in this section.

In Section 2.3 the Optical Transport Network (OTN) is briefly explained, in order to understand how the information (Optical Transport Unit (OTU)) is transported in an optical network.

In Section 2.4 the ROADM network element is analyzed. We will go through the ROADM evolution, his main components, mainly the WSS and the add/drop structures, and finally, we will characterize the two most used architectures, the Broadcast-and-Select and the Route-and-Select.

Finally, Section 2.5 summarizes the main conclusions of this chapter.

2.2. Network Topologies

A telecommunications network is a collection of terminal nodes, links and many intermediate nodes which are connected in order to enable communication between the terminal nodes. A network can be described by a graph ***G*(*V*,*E*)** where ***V*** denotes the set of nodes or vertices ($V = (v_1, v_2, v_3 \ldots v_n)$), and ***E*** denotes the set of links or edges ($E = (e_1, e_2, e_3 \ldots e_n)$) [4]. Figure 2.1, below, shows a simple network graph with 5 vertices (nodes) and 7 edges (links).

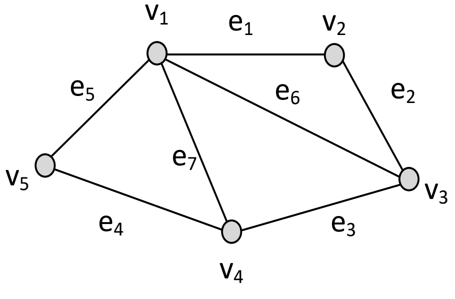


Figure 2.1: Simple network graph with 5 nodes and 7 links.

A link is defined as a connection between two nodes (e.g. $e_1 = (v_1, v_2)$) and it can be unidirectional or bidirectional. Normally, a bidirectional link can be implemented with two unidirectional links. An optical link can include optical fibers and optical amplifiers (OA) (the OAs are not considered as nodes). The section of the link between a node and an OA is called a span, as shown in Figure 2.2 [4].

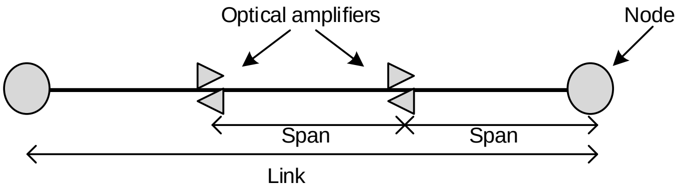


Figure 2.2: The basic elements in an optical network.

A network graph with bidirectional links is called undirected graph, whereas a network graph with unidirectional links is called a directed graph. Figure 2.3(a), below, shows a simple undirected graph, whereas Figure 2.3(b) shows a directed graph.

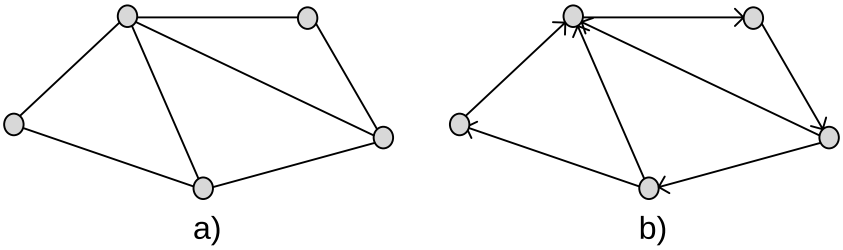


Figure 2.3: Network graph example of – a) an undirected graph and b) a directed graph.

A path is a sequence of links, which starts at a node ***s*** and ends at a node ***t*** (path ***s-t***). A path may be also undirected or directed depending if their links are bidirectional or unidirectional links. If ***s*** and ***t*** are the same, then the path is called a cycle. In optical networks a path is called a lightpath. Typically, an optical path is implemented using a wavelength. Thus, as shown in the Figure 2.4, for example the path $v_1 \rightarrow v_4$ is $\{e_1, e_2, e_3\}$ and the cycle for node v_1 is $\{e_1, e_2, e_3, e_4, e_5\}$. A path can be also represented by the sequence of nodes traversed, for example the path $v_1 \rightarrow v_4$ can be represented by $\{v_1 - v_2 - v_3 - v_4\}$ [4].

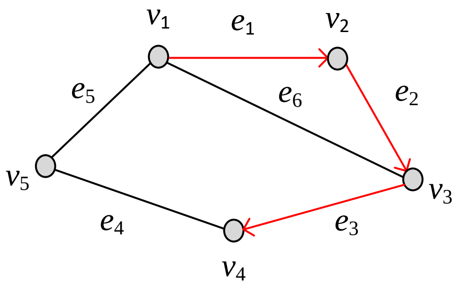


Figure 2.4: Representation of the path $v_1 \rightarrow v_4$ in red.

A path is used to carry traffic. Traffic is defined as the set of services (*e.g.* data, video, voice) that is carried on the network. A demand is used to represent an individual request for traffic and corresponds to a logical link. In unicast applications demands are between two nodes and can be bidirectional and symmetric (this is the scenario used in this dissertation). An example of a bidirectional traffic demand is shown in Figure 2.5.

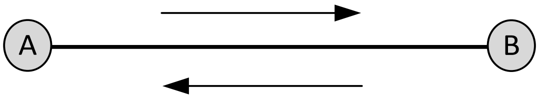


Figure 2.5: Bidirectional traffic demand between nodes A and B.

A connection represents a path that has been reserved for carrying a demand.

Nodes are the equipment (*e.g.* ROADMs) used in network for routing the optical signals through the chosen lightpath.

Physical and logical topologies

The physical interconnection between nodes defines the physical topology of the network. In an optical network we have, typically, optical fibers for the links and ROADMs for the nodes. Figure 2.6 represents an example of a physical topology. In this figure we can see that the physical topology is a partial mesh.

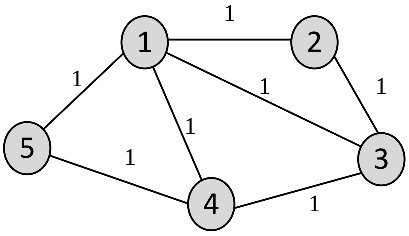


Figure 2.6: Partial mesh physical topology example.

The network physical topology can be represented by a graph ***G*(*V*,*E*)**, or through an adjacency matrix *g*. This matrix has an $N\times N$ (*N* is number of nodes) dimension. The link $g_{ij} = 1$ defines a physical connection between *i* and *j*, while $g_{ij} = 0$ means that does not exist a link between *i* and *j*. The cost matrix *c* represents the cost of each link. The following matrices *g* and *c* (Equation (2.1)) show, respectively, the adjacency matrix and cost matrix, for the physical topology illustrated in Figure 2.6. In this figure the cost of each link represents the number of hops, but other metrics can be used, such as the bit rate.

$$g = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{bmatrix} \qquad c = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{2.1}$$

The logical topology describes how traffic flows through the network. Figure 2.7 shows an example of a possible traffic pattern in the physical topology represented in Figure 2.6. In this scenario we have a star logical topology. Traffic can be described by the number of traffic demands or logical links. Traffic requests can be unidirectional or bidirectional.

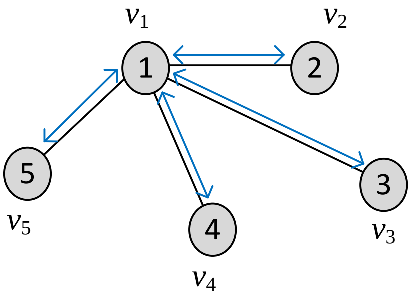


Figure 2.7: Star logical topology (bidirectional representation) example.

The logical topology can be also described by the demand matrix ***d***, given by Equation (2.2). The element $d_{ij} = 1$ if there is a traffic request between i and j, and $d_{ij} = 0$ otherwise.

$$d = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (2.2)$$

The traffic matrix describes the volume of traffic during a period of time between node ***s*** (source) and node ***d*** (destination).

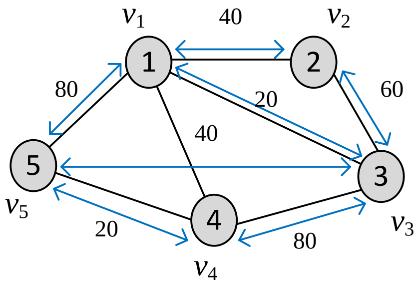


Figure 2.8: Example of a bidirectional traffic flow between different nodes.

Figure 2.8 represents an example of the traffic between the various nodes in the network and the number above the links represent the amount of traffic transported (*e.g.* between node v_5 *e* v_3 a total of 40 units of traffic is transported). The amount of traffic can be also represented in a matrix notation, as illustrated in Equation (2.3), (matrix *t*), where the traffic generated in the network of Figure 2.8 is shown.

$$t = \begin{bmatrix} 0 & 40 & 20 & 40 & 80 \\ 40 & 0 & 60 & 0 & 0 \\ 20 & 60 & 0 & 80 & 0 \\ 40 & 0 & 80 & 0 & 20 \\ 80 & 0 & 0 & 20 & 0 \end{bmatrix} \tag{2.3}$$

Types of network topologies

The network topology type condition the development strategy and the type of services that the network will offer. There are several types of topologies [5]. Next, we will briefly describe the bus, star, ring, tree and mesh topologies, which are the most common topologies in telecommunication networks.

Bus topology – In a bus network all nodes are connected directly to the bus through which the information circulates, so all nodes in the network can receive all the information that is transmitted in the network. In Figure 2.9 we can see an example of the bus topology [5]. The bus topology is used in local area networks.

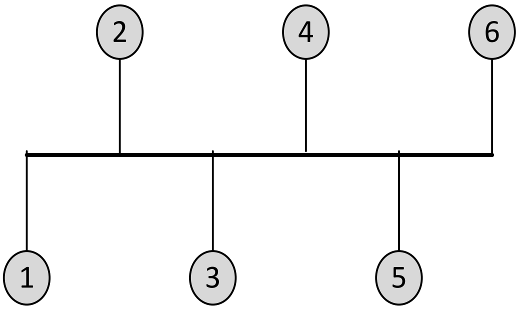


Figure 2.9: Bus topology example.

Star topology – As the name implies this topology has the shape of a star and consists of several fibers that attach each node to a central node, as can be seen in the Figure 2.10 [5]. The star topology is used, also, in local area networks.

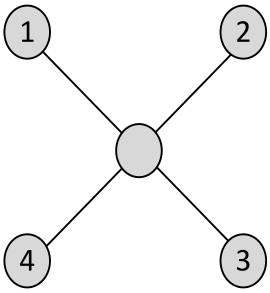


Figure 2.10: Star topology example.

Ring topology – In the unidirectional ring topology the information circulates through all the nodes of the network, as shown in Figure 2.11. An example of the transmission of information between nodes 1 and 3 and 3 and 1 is represented in this figure. Ring topologies are typically used in metropolitan networks (*e.g.* Synchronous Digital Hierarchy (SDH) ring networks) [5].

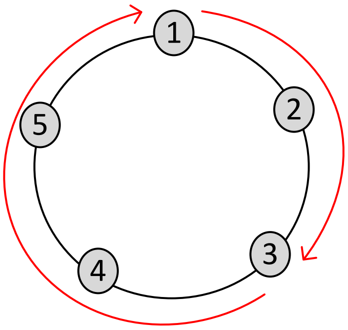


Figure 2.11: Ring topology example.

Tree topology – It has a root node and all other nodes are connected to it forming a hierarchy. It is also called hierarchical topology and it should at least have three levels in the hierarchy, as shown in Figure 2.12. Tree topologies are usually used in Passive Optical Networks (PONs).

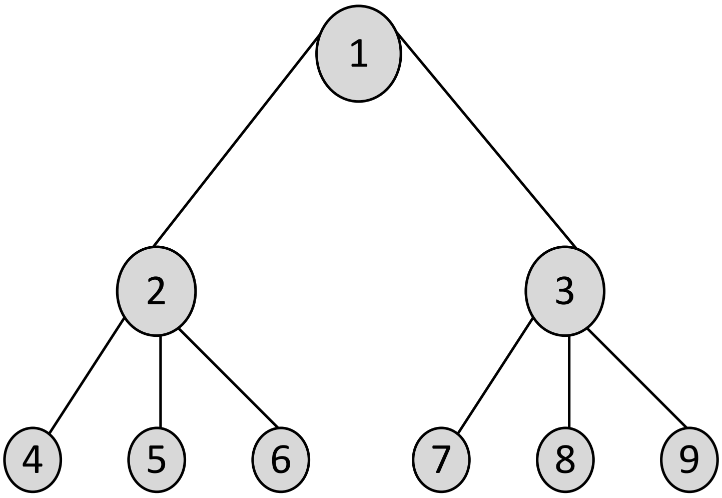


Figure 2.12: Tree topology example.

Mesh topology – The mesh network consists of several nodes that are connected to several other nodes of the network, as illustrated in Figure 2.13. If every node is connected to all of the other nodes, then we have a full mesh topology [5]. This topology is widely used in core networks.

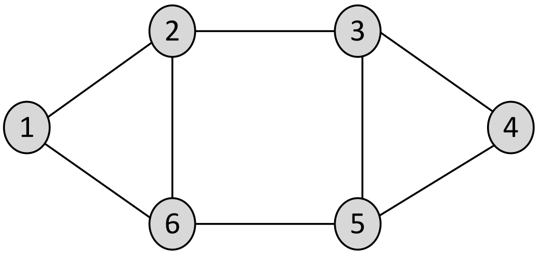


Figure 2.13: Mesh topology example.

2.3. Optical Network Architecture

A telecommunication network can be structured in two layers, the service layer and the transport layer as shown in Figure 2.14. The top layer is the service layer and it is the client of the transport layer, which is responsible for choosing the path for the service layer. Nowadays, typically, all the information is Internet Protocol (IP) packets and these packets can be transported in the electrical domain by a SDH transport network, or by a Multi-Protocol Label Switching (IP/MPLS) transport network. This SDH frames or IP/MPLS packets can then be further encapsulated in OTN frames when they enter an optical network [6], [7].

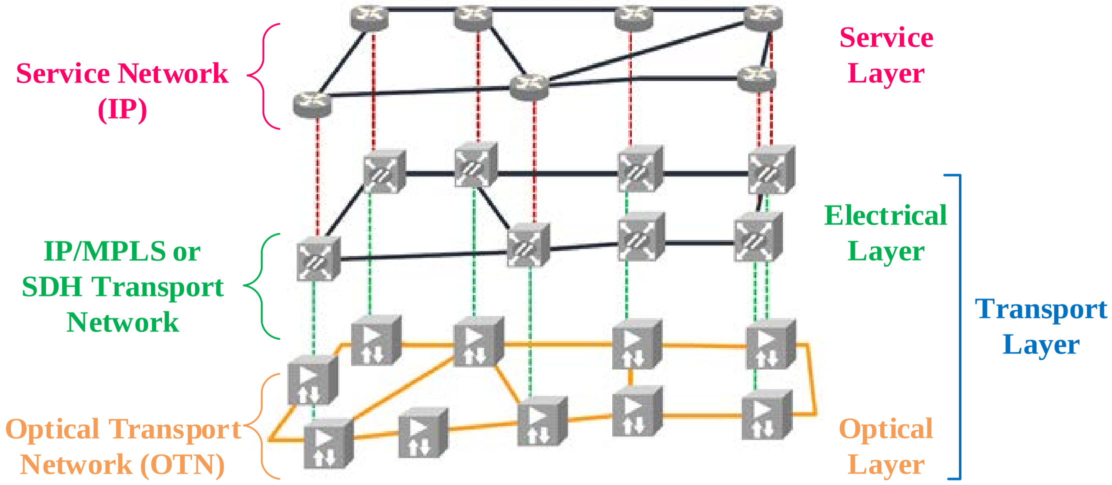


Figure 2.14: Layered telecommunication network architecture.

OTN defined in ITU G.872 extends the benefits of other transport technologies, such as the SDH, for increased transmission capacity and distances [7]. OTN offers the following advantages over SDH: 1) Stronger Forward Error Correction (FEC); 2) Optical monitoring capacity [8]. It structure comprises of two main domains: electrical and optical as shown in Figure 2.15.

The electrical domain is responsible for mapping the tributary signals (IP packets, SDH frames) into a fixed length frame and adding the appropriate headers, leading to the formation of the Optical Transport Unit (OTU-k) entity. The value of ***k*** is associated with the bit rate of the OTUs. (OTU-1: ≈ 2.67 Gb/s; OTU-2: ≈ 10.7 Gb/s; OTU-3: ≈ 43 Gb/s [4]. The optical domain is responsible for the formation of the optical channel, multiplexing and the introduction of appropriate headers and leads to the formation of the OTM-n.m (Optical Transport Module) entity where ***n*** represents the number of optical channels and ***m = 1*** to 2.5 Gbps, ***m = 2*** for 10 Gbps, ***m = 3*** for 40 Gbps, ***m = 12*** for channels with mixed rate, 2.5 and 10 Gbps, ***m = 23*** for channels with mixed rate, 10 and 40 Gbps and ***m = 123*** for channels with mixed rate, 2.5, 10 and 40 Gbps [4], [9].

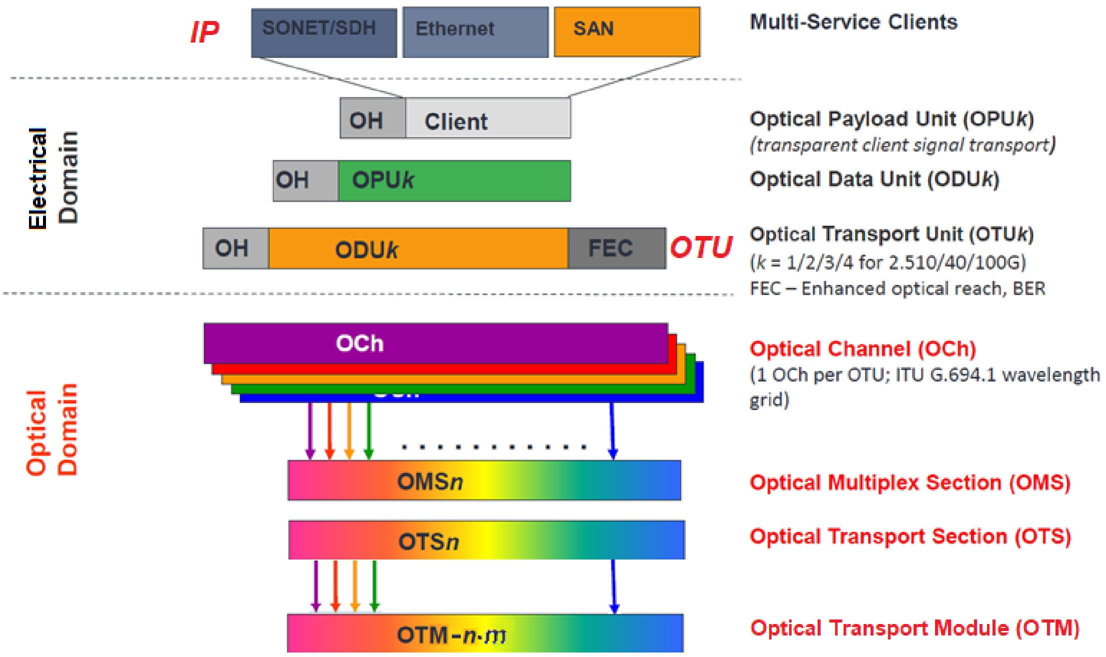


Figure 2.15: Optical Transport Hierarchy [10].

2.4. Reconfigurable Optical Add/Drop Multiplexers (ROADM)

A ROADM is an example of a network node that allows for dynamically express, add and drop wavelengths.

ROADM technology has achieved a considerable growth in some developed countries and regions. This is largely due to the fact that several important operators have shown great interest in upgrading their networks to become more flexible and cost effective [11].

2.4.1. Evolution

In the earliest times of optical networks, the nodes were not reconfigurable and they were called optical add/drop multiplexers (OADMs). There were two ways to built the OADMs, the series and parallel architecture, as shown in Figure 2.16 and Figure 2.17, respectively.

In the parallel architecture shown in Figure 2.16 all wavelengths are demultiplexed by using, for example, an AWG, some being added/dropped and other transmitted through the OADM. The losses introduced by the OADM are constant and independent of the number of extracted channels. This configuration ensures a perfect harmony between the pair multiplexer/demultiplexer and allows building OADMs with capacity to add/drop up to 256 channels [11].

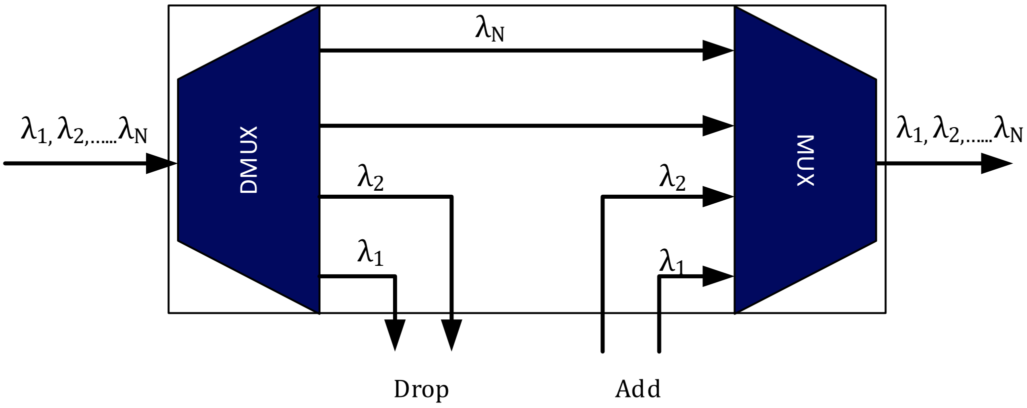


Figure 2.16: OADM parallel architecture [6].

In the series architecture, shown in Figure 2.17, the wavelengths are added/dropped one by one using a single channel OADM (OADM SC).

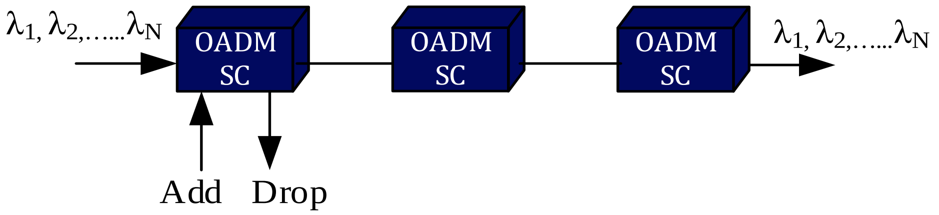


Figure 2.17: OADM series architecture [6].

In the first generation of ROADMs an optical switch was placed between the Demultiplexer (DEMUX) and Multiplexer (MUX), that basically express, extract or insert wavelengths according to the switch state (bar or cross), as shown in Figure 2.18. A transponder is used to insert the client signals in an optical network, or to extract the optical signals and deliver them to the clients. His main functions are wavelength adaptation, adding/removing headers, adding/removing FEC codes, and Bit Error Rate (BER) monitoring. These ROADMs were used, typically, in ring networks [4].

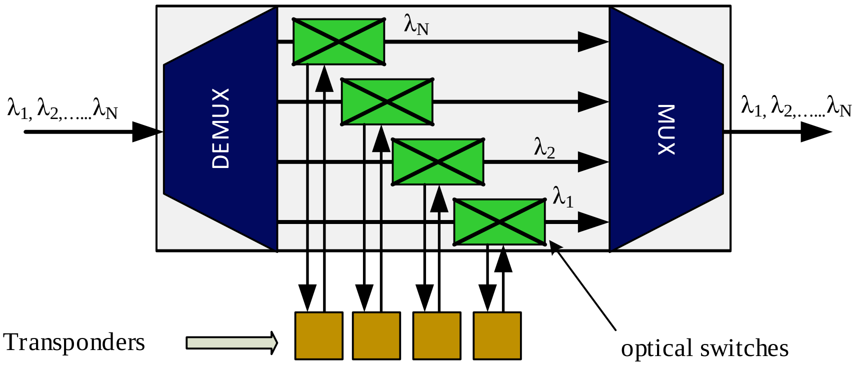


Figure 2.18: First generation ROADM architecture.

The second generation of ROADMs is shown in Figure 2.19. The difference between the first and second generations is that the second one applies wavelength blocking technology, which makes it better in terms of isolation than the first generation [4]. A tap is used to drop any number of selected wavelengths. All wavelengths enter the blocker and the wavelengths that pass-through are not blocked. Finally, a combiner is used to add wavelengths in the tap to get into the output fiber [11].

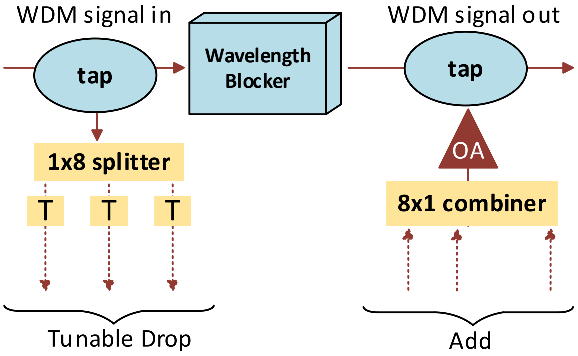


Figure 2.19: Second generation ROADM architecture [11].

A ROADM wavelength blocker can pass, or block any or all of the wavelengths. The wavelength blockers were used primarily in mesh long-haul WDM networks, regional and metropolitan networks [11].

The great disadvantage of these earlier generations of ROADMs was the incapability for having more than 2 degrees, which is achieved in the third generation with the introduction of the WSSs. The WSS is an active component that performs switching, multiplexing, demultiplexing and wavelength monitoring [11], as illustrated in

Figure 2.20. This component will be discussed in more detail in the next sub-section. With these components multi-degree ROADMs can be built. An example of a third generation ROADM is illustrated in Figure 2.20, where a WSS is used at the ROADM input stage.

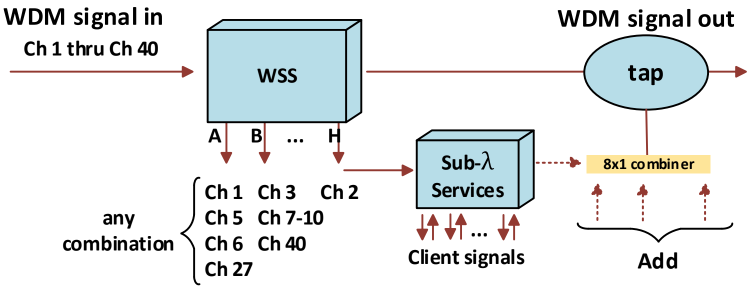


Figure 2.20: Third generation ROADM architecture [11].

2.4.2. ROADM Components

The WSS is the core element of modern ROADMs. A WSS can be composed of multiplexer and demultiplexer based on AWG technology and optical switches based on MEMS or Liquid Crystal on Silicon (LCoS) technology. It can dynamically route or block all WDM wavelengths within a network node, as shown in Figure 2.21.

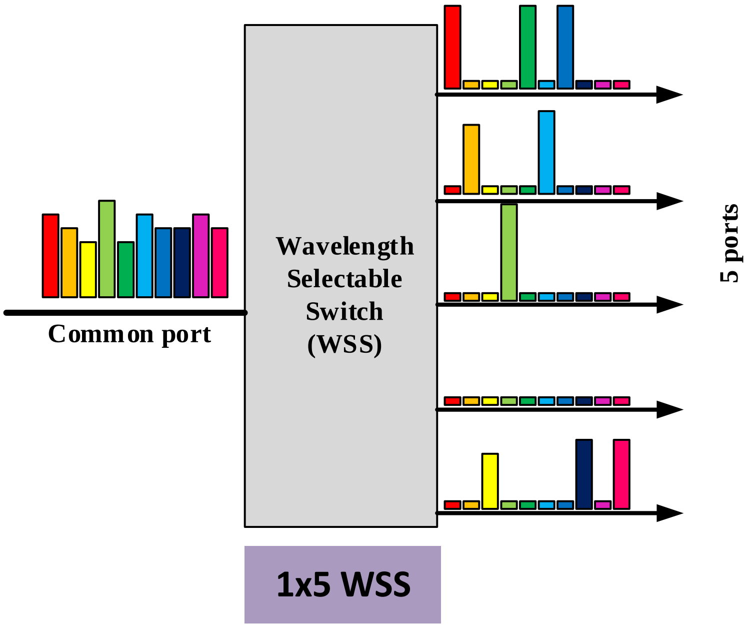


Figure 2.21: Functional diagram of a 1×5 WSS providing one input port, and 5 outputs ports.

The function of the WSS is as follows: the input fiber has multiple wavelengths (*i.e.* WDM signal) and this component has the ability to choose which is the wavelength that should be in each of the outputs. This wavelength routing process can be changed dynamically through an electronic control interface.

In Figure 2.22 we show the components that are used for building the WSS. The 1×N WSS of Figure 2.22 has one input and N outputs. It is composed by a demultiplexer which can be constituted, for example, by an AWG, which will demultiplex the input signal and then goes through K 1×K (K is number of wavelengths in the WDM input signal) switches (*e.g.* MEMS technology). In each output there is a multiplexer that will bring together all of these signals and put them in the N possible outputs [12].

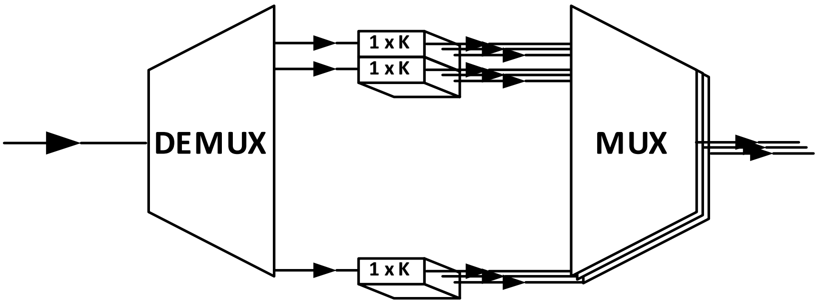


Figure 2.22: WSS components: DEMUX, MUX and optical switches.

The vast majority of WDM technologies, *e.g.* AWG and MEMS, while allowing significant routing and switching functionality, do not allow for the possibility for variable passband widths. AWGs and MEMS devices are inherently fixed grid WDM devices with their fixed channel granularity (for example, 50 GHz) defined at the time of their manufacture. In contrast, liquid crystal-based technologies have matured in recent years and using the holographic principle can offer flexible passband filtering in conjunction with the wavelength switching and routing functionalities required for a flex-grid WSS. In this case, the key component within the WSS is a LCoS device, to enable active switching and beam steering of light [13].

Besides the WSS, ROADM nodes must have an add/drop structure for adding and extracting optical signals to and from the optical network. In the following we will present basically three properties that characterize the add/ drop structure of a ROADM: **Colorless**, **Directionless** and **Contentionless** [11], [14].

Colorless – it means that we can insert or extract any wavelength in any port, (*i.e.* a port is insensitive to color and so a port does not have a fixed wavelength). The earlier add/drop structures of ROADMs were colored. In these add/drop structures, a specific wavelength must be connected to its port on an add/drop multiplexer, and that multiplexer is only associated with a single fiber direction. These restrictions in the add/drop structure limit wavelength assignment and the ability to dynamically assign wavelengths to a particular fiber direction. In Figure 2.23 we show a colorless 4-degree ROADM, since both in the add and drop structure there are no restriction on the wavelength color. In the add section we have a combiner and in the drop section we have a WSS.

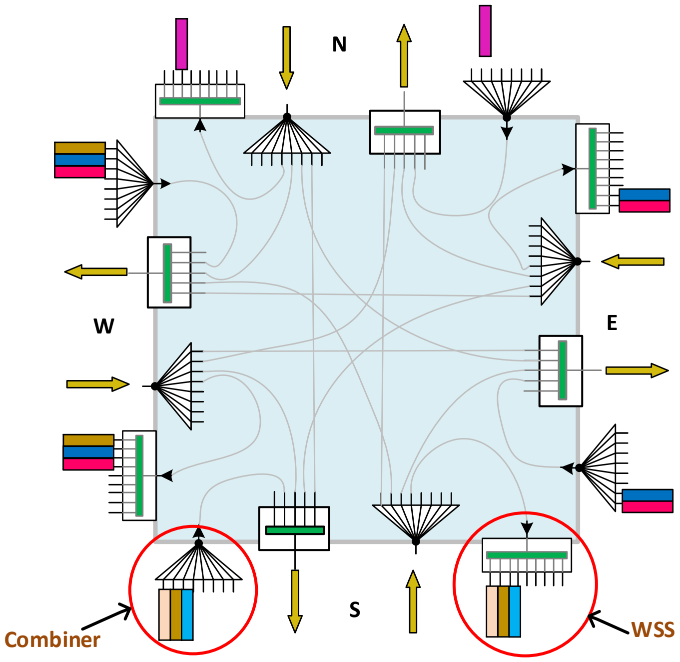


Figure 2.23: Colorless-ROADM with 4 degrees.

Directionless – it means that the input signals are not directed only to a specific direction, but to all directions of the ROADM, *i.e.* any wavelength inserted in a port may be directed in any direction, as shown in Figure 2.24. The ROADM add/drop structure of Figure 2.24 which is colorless and directionless consists on a combiner/splitter on the add section and a cascade of $D\times1$ and $1\times K$ WSS (D is the ROADM degree and K is the number of wavelengths in each fiber on the drop section).

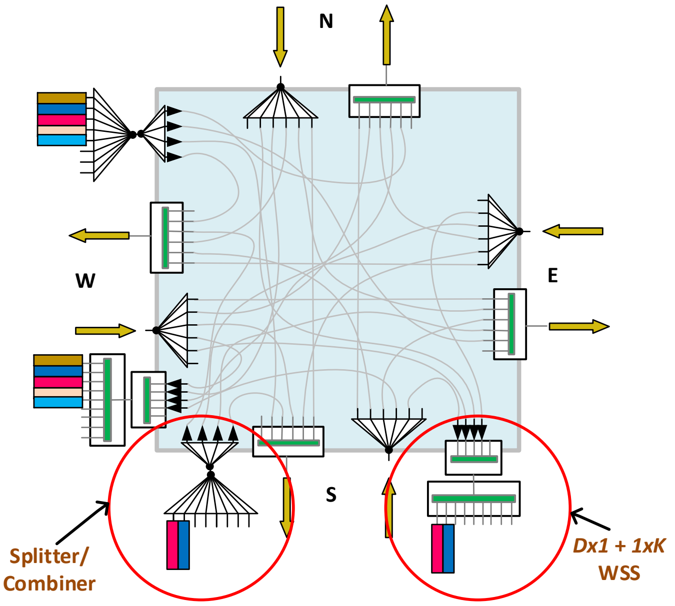


Figure 2.24: Colorless and Directionless-ROADM with 4 degrees.

Contentionless – besides the colorless and directionless features the ROADM can be contentionless which means that an add/drop structure can add/drop signals with the same wavelength. To implement this feature an $M \times N$ WSS is used in some of the directions of the ROADM, as shown in Figure 2.25.

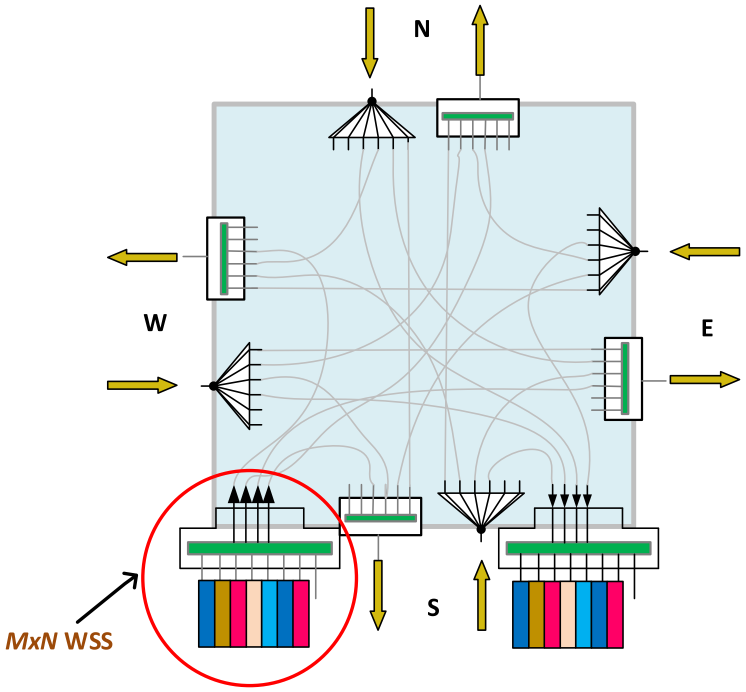


Figure 2.25: Colorless, Directionless and Contentionless-ROADM with 4 degrees.

2.4.3. ROADM Architectures

In this section the two most important ROADM architectures are presented and compared: Broadcast-and-Select and Route-and-Select [1].

The architecture Broadcast-and-Select has this name because when the WDM signal enters the splitter (power divider) the signal is sent to all the outputs, *i.e.* the input signals are replicated in all output WSS and drop ports, as shown in Figure 2.25.

A disadvantage of this architecture is the insertion losses in the splitter, because the input power will be divided by number of outputs and when this number is large the power losses are greater.

In the Route-and-Select architecture we replace the input splitter by an 1×*N* WSS. The great advantage of this architecture is the reduction of the insertion losses since we are not using a splitter, as shown in Figure 2.26. A disadvantage of this architecture is the cost.

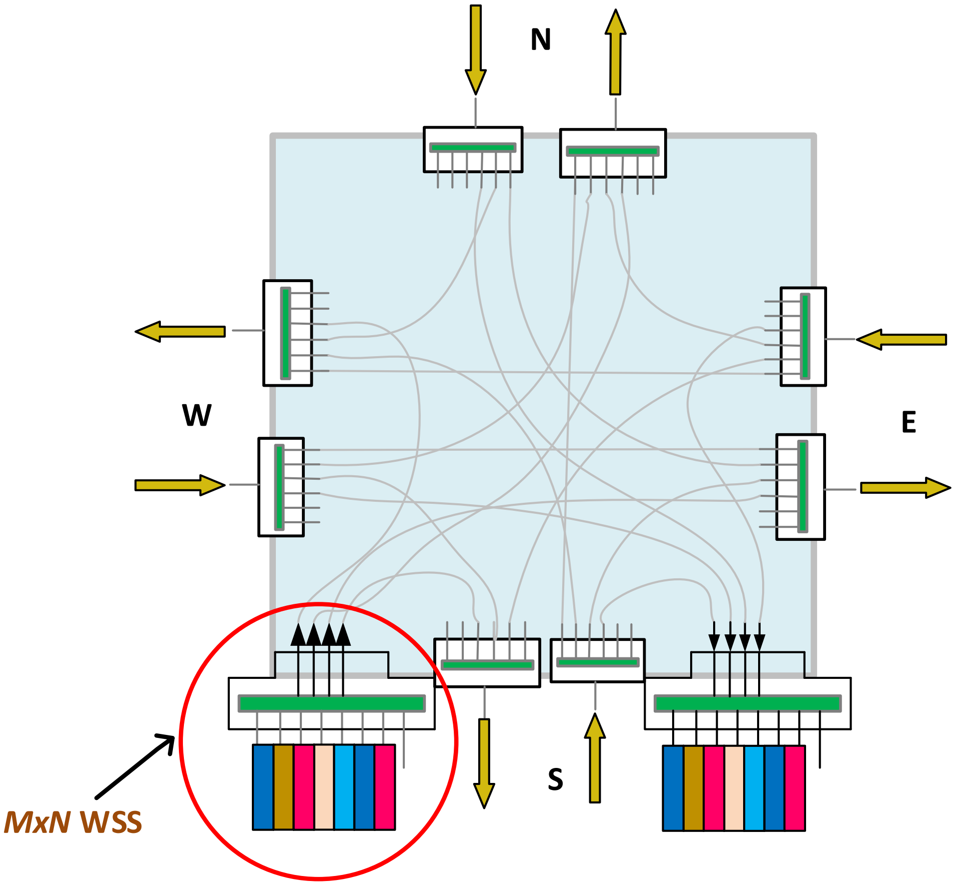


Figure 2.26: Route-and-select architecture example.

2.5. Conclusions

In this chapter we have described a set of basic optical network concepts. We have also briefly explained the Optical Transport Network (OTN) architecture.

Then we described the ROADM evolution, with a focus on the WSS, add and drop structures, and their properties (colorless, directionless and contentionless). Finally, we have presented the ROADM architectures, namely the Broadcast-and-Select and Route-and-Select architecture.

Chapter 3 – Network Planning Tools

3.1. Introduction

In this chapter, the RWA problem is studied for static networks. Static networks correspond to the scenario where the traffic matrix does not change over time. And, on the other side, dynamic networks corresponds to the scenario in which the traffic matrix varies over time, *i.e.* the arrival and termination of new paths orders is a function of time.

In this dissertation the RWA problem will be solved with heuristic solutions, instead of optimal solutions. Heuristic solutions are, mainly, used to save computation time. The goal of a heuristic solution is to find a solution in a reasonable time period that is good enough for the problem in question. An optimal solution, typically, requires high computing times, especially for large networks [15].

In this dissertation heuristic solutions are used for both routing and wavelength assignment (WA) problems. For routing, the shortest path algorithm will be studied in Section 3.3, and for WA the Graph Coloring, First-Fit and Most-Used algorithms are going to be discussed in Section 3.5. Several ordering strategies will also be studied in Section 3.4.

Survivability, a critical aspect in optical networks, will also be analyzed in Section 3.6.

Finally, in Section 3.7, some simple network scenarios with and without protection are studied to validate and test our planning tool simulator.

3.2. RWA Planning Tool

In this section the RWA problem is discussed for a static network scenario, based on heuristic solutions. Graph Coloring, First-Fit and Most-Used algorithms, are used and implemented to assign wavelengths to the lightpaths, whereas the Dijkstra algorithm is used for routing.

The flowchart shown in Figure 3.1 shows how the RWA problem is decomposed and implemented. It is broken down into five sub-problems:

1) The network physical topology defined by the adjacency matrix or the cost matrix and the logical topology defined by the traffic matrix consist on the first sub-problem.

2) The mapping between the logical and physical topologies is done using the Dijkstra shortest path algorithm and consists on the lightpath routing sub-problem.
3) The third sub-problem deals with the traffic routing where different traffic units are routed and assigned between the source and destination edge nodes over the logical topology (only one traffic unit is considered in this dissertation – a OTU-4 is used for the traffic unit).
4) The fourth sub-problem consists on ordering the paths before wavelengths are assigned to the paths, that are defined by the routing algorithm. The paths are ordered using various ordering strategies. These strategies are based on the "length" of the lightpath such as Shortest Path First (shortest "length" is assigned first), Longest Path First (assign the "longest" path first) and Random Path Order (paths are randomly ordered). The "length" of the path can be, for example, the distance in km, or the number of hops.
5) Finally, after ordering the lightpaths using the previously mentioned strategies, it is time to assign wavelengths using the various WA heuristic algorithms, such as Graph Coloring, First-Fit and Most-Used.

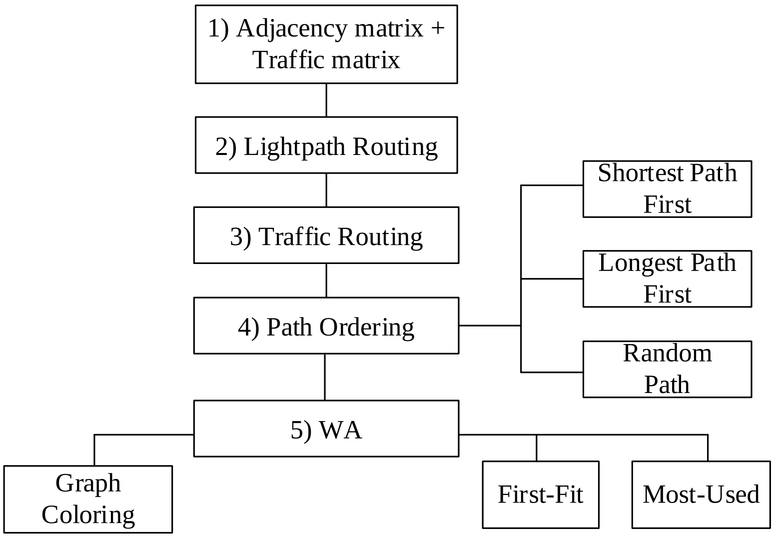


Figure 3.1: The five RWA sub-problems (this figure was adapted from Figure 3.1 of [28]).

3.3. Routing Algorithms

The goal of the routing algorithm is to map the logical topology on the physical topology. In particular, the goal of the shortest-path routing algorithm is choosing the path with the minimal cost. The shortest-path routing problem is usually solved by two classical algorithms: (a) the Bellman-Ford algorithm and (b) the Dijkstra's algorithm [16].

The Dijkstra’s algorithm finds out paths with links whose sum of their weights is the smallest possible [1]. The sum of the links cost can be the number of hops, the distance in km or the Optical Signal-to-Noise Ratio (OSNR) of that path. These measures are called the routing metrics. The Dijkstra’s algorithm is presented below as Algorithm 1 [17].

Algorithm 1: Dijkstra Shortest Path

Inputs:

netCostMatrix: weighted undirected graph, with set of vertices ***V*** and set of edges ***E***;

***s*:** source node index;

d: destination node index;

Outputs:

shortestPath: the list of nodes in the shortest path from source to destination;

totalCost: the total cost of the shortest path;

Data:

S: set of nodes for which the shortest path has already been resolved;

Q: the queue initially contains all vertices unresolved;

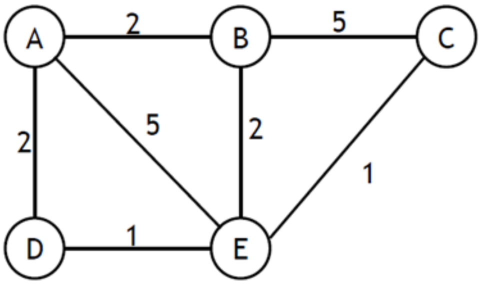
u: node in analysis

$d(u)$: cost to node ***u*** from node ***s***, equal to the sum of the edge costs on path from ***s*** to ***u***;

$w(u, v)$: cost of directed edge from node ***u*** to node ***v***.

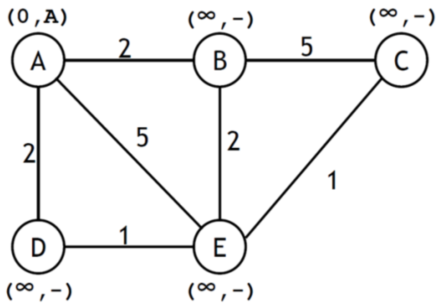
```
$S \leftarrow \{\ \}; Q \leftarrow V[G]; d(v) \leftarrow \infty; d(s) = 0$
while $(Q \neq \{\ \})$
    $u \leftarrow min_d \{\ \}$
    $Q \leftarrow Q \{u\}$
    $S \leftarrow S \cup \{u\}$
    for each $v \in adj_Q[u]$ do:
        if $d(v) > d(u) + w(u, v)$
            then $d(v) = d(u) + w(u, v)$
```

An example of the use of the Dijkstra algorithm is present below considering a 5 node network with the physical topology shown in Figure 3.2(a). In this example we want to find the shortest path between nodes *A* and *C* as shown in Figure 3.2 (b), (c), (d), (e), (f) and (g).



(a)

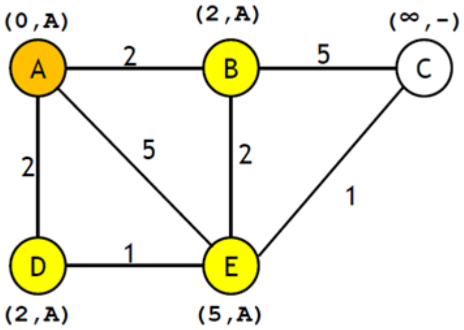
$S \leftarrow \{\ \}; Q \leftarrow V[G];$
$d(v) \leftarrow \infty;$
$d(s) = 0$



(b)

$S = A; S \leftarrow \{\ \};$
$Q \leftarrow \{A, B, C, D, E\}$

```
while ($Q \neq \{\ \}$)
    $u \leftarrow min_d(Q)$
    $Q \leftarrow Q \{u\}$
    $S \leftarrow S \cup \{u\}$
    for each $v \in Adj_Q[u]$ do:
        if $d(v) > d(u) + w(u, v)$
            then $d(v) = d(u) + w(u, v)$
```



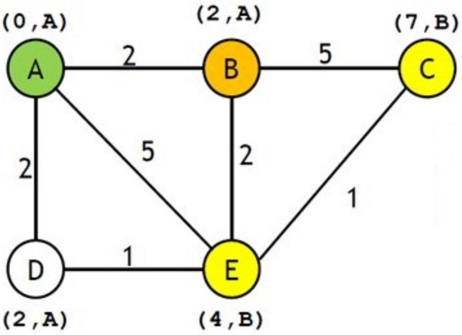
(c)

u=A,
v=B, dv=$d(B)$=∞
∞ $d(B) > 0\ d(A) + 2\ w(A,B)$
$d(B)$=2

v=E, dv=$d(E)$=∞
∞ $d(E) > 0\ d(A) + 5\ w(E,A)$
$d(E)$=5

v=D, dv=$d(D)$=∞
∞ $d(D) > 0\ d(A) + 2\ w(D,A)$
$d(D)$=2

$u \leftarrow min_d(Q) = B$
$S \leftarrow \{A, B\}$
$Q \leftarrow Q \{D, E, C\}$
$Adj_Q[u] \leftarrow \{C, E\}$

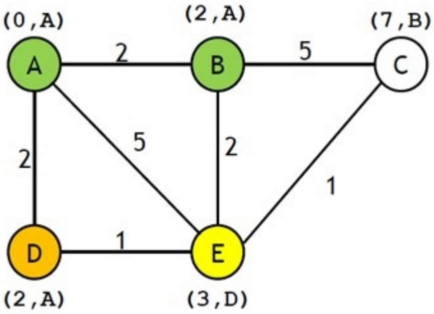


(d)

u=B,
v=E, dv=$d(E)$=5
5 $d(E) > 2\ d(B) + 2\ w(B,E)$
$d(E)$=4

v=C, dv=$d(C)$=∞
∞ $d(C) > 2\ d(B) + 5\ w(B,C)$
$d(C)$=7

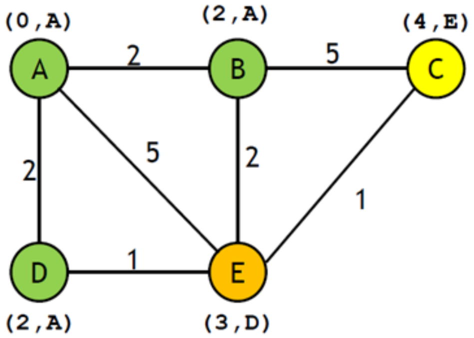
$u \leftarrow min_d(Q)$ = D
$S \leftarrow \{A, B, D\}$
$Q \leftarrow Q \{E, C\}$
$Adj_Q[u] \leftarrow \{E\}$



(e)

u=D,
v=E, dv=$d(E)$=4
4 $d(E) > 2\ d(D) + 1\ w(D,E)$
$d(E)$=3

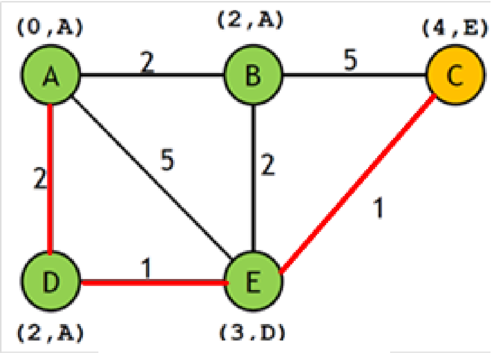
$u \leftarrow min_d(Q)$ = E
$S \leftarrow \{A, B, D, E\}$
$Q \leftarrow Q\{C\}$
$Adj_Q[u] \leftarrow \{C\}$



u=E,
v=C, dv=$d(C)$=7
7 $d(C)$ > 3 $d(E)$ + 1 $w(E,C)$
$d(C)$=4

(f)

$u \leftarrow min_d(Q)$ = C
$S \leftarrow \{A, B, D, E, C\}$
$Q \leftarrow Q\{\}$
$Adj_Q[u] \leftarrow \{\}$



(g)

Figure 3.2: Dijkstra algorithm example for finding the shortest path between *A* and *C*.

In Figure 3.2(d) the choice between nodes *B* and *D* as the next node ***u*** is arbitrary. If the choice had been otherwise it could result in a different flowing tree, yet they would be equally optimal (*i.e.* none would be better than the other).

In summary, from Figure 3.2, we can conclude that whenever we propose to visit a new node (*u*), we will choose the node (*u*) with the lowest known distance/cost to be visited first. As soon as we move to the node we are going to visit, we'll check each of the neighboring nodes. For each neighbor node, we will calculate the distance/cost for the neighboring nodes adding the cost of the edges that lead to the node that we are checking from the initial vertex $[d(u) + w\ (u, v)]$. Finally, if the distance/cost for a node is less than the known distance, we will update the shortest distance we have calculated for that vertex [if $d(v) > d(u) + w\ (u, v)$ then $d(v) = d(u) + w\ (u, v)$]. In the example given in Figure 3.2 we can conclude that the shortest path between nodes A and C has a cost of 4 and has the following path $ADEC$.

3.4. Ordering Strategies

In a static network scenario we have a set of paths to assign wavelengths at a particular instant of time, so a strategy for ordering the paths is needed for wavelength assignment. In the case of dynamic networks we have only one wavelength to assign at a particular time instant, so there is no need for such an ordering strategy in these kind of networks.

The ordering strategies used by the wavelength assignment heuristics algorithms, the First-Fit and Most-Used discussed in Section 3.5, are:

- Shortest Path First: the paths with the smallest number of hops/cost between the source and the destination are ordered in the first place.
- Longest Path First: the paths with the highest number of hops/cost between the source and the destination are ordered in the first place.
- Random Path Order: the paths are randomly ordered.

3.5. Wavelength Assignment Algorithms

In this section, the WA problem for static networks is presented and several WA algorithms are studied. Every WA algorithm must satisfy the following two features: 1) two optical paths should not have the same wavelength if they use common links; 2) the same wavelength is used in all links of a path (wavelength continuity). The main goal of the WA problem in a static network scenario is to minimize the number of assigned wavelengths. In this section the Graph Coloring, the First-Fit and Most-Used are the WA algorithms studied. The last two algorithms are usually applied to dynamic networks, but they may be also applied to static networks by ordering the lightpaths and then sequentially assigning wavelengths to the ordered lightpaths. Several ordering strategies are used as discussed in Section 3.4. We will start by explaining the Graph Coloring algorithm [2].

3.5.1. Graph Coloring

The Graph Coloring is a conventional mathematical problem that consists in coloring all nodes of a graph so that there are no two adjacent nodes with the same color [2]. The Graph Coloring algorithm can be used for wavelength assigning in optical paths [1], [16].

In optical networks this algorithm has the following three steps:

Step (1): The first step consists on transforming the network graph $\boldsymbol{G(V,E)}$ into a network graph $\boldsymbol{G(W,P)}$, whose nodes are optical paths ($\boldsymbol{W = (w_1, w_2, w_3 \ldots\ldots w_M)}$), and $\boldsymbol{P}$ represents the set of links between these nodes. There is an undirected edge between two nodes in graph ***G*(*W*,*P*)** if the corresponding lightpaths have common links. Figure 3.3 represents a 5 node ring network where a certain number of paths is defined. Figure 3.4 represents the corresponding graph ***G*(*W*, *P*)**, where each node represents a path [18].

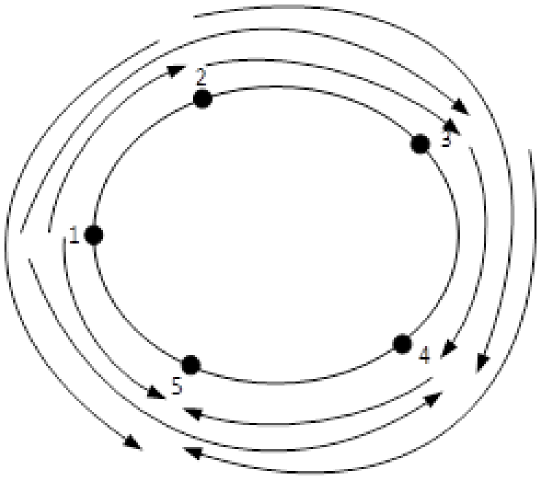


Figure 3.3: Graph *G* (*V*,*E*) of a 5 node ring network with the paths represented as line arrows.

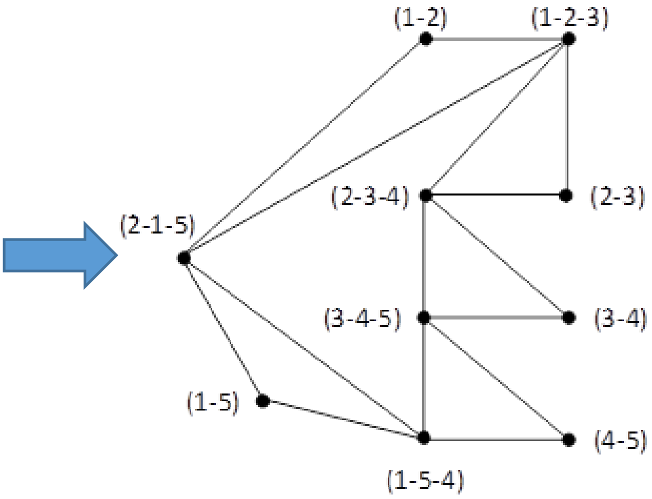


Figure 3.4: Graph *G*(*W*,*P*) of the network represented in Figure 3.3.

The procedure to obtain ***G*(*W*,*P*)** from ***G*(*V*,*E*)** is presented in Algorithm 2. The goal of Algorithm 2 is to transform the graph ***G*(*V*,*E*)** of Figure 3.3, (where the paths shown in the figure where obtained using Algorithm 1 (Dijkstra)), in a graph of paths ***G*(*W*,*P*)** of Figure 3.4.

Algorithm 2: Build graph ***G*(*W*,*P*)** from ***G*(*V*,*E*)**

Inputs:

tabPath: table whit the paths calculate using Algorithm 1 (Dijkstra);

Outputs:

GadjMatPath: adjacency matrix of paths to use for coloring the nodes;

data: v_i and v_j are vertices of ***GadjMatPath***;

```
foreach $p_x \in tabPath$ do
  foreach $p_y \in tabPath$ do
    if $tabPath(p_x, p_y+1) \neq 0$
        $v_i \leftarrow tabPath(p_x, p_y)$
        $vj \leftarrow tabPath(p_x, p_y+1)$
          while $k \in tabPath$ do
            while $l \in tabPath$ do
              if $(tabPath(k,l)=v_i \cap tabPath(k,l+1)=v_j) \cup (tabPath(k,l)=v_j \cap tabPath(k,l+1)=v_i)$
                  $GadjMatPath(p, k) \leftarrow 1$
                  $GadjMatPath(k, p) \leftarrow 1$
return GadjMatPath
```

Step (2): The second step consists in choosing the ordering strategy for coloring the nodes. Several strategies can be defined for this algorithm:

- Greedy Strategy: in this strategy the vertices (nodes) are placed in descending order of degree. Degree is the number of edges incident to the vertex. This is the strategy implemented in Algorithm 3 (defined in step 3).
- Random Strategy: puts vertices in random order.
- Optimal Strategy: always finds a minimum number of colors. Graph Coloring is known to be a difficult problem in finding an optimal solution for large graphs [2].

Table 3.1: Ordered list of the different vertices in descending order of their degree for the *G*(*W*,*P*) of Figure 3.4.

Paths	Degree	Wavelength
1-2-3	4	λ_1
2-3-4	4	λ_2
3-4-5	4	λ_1
1-5-4	4	λ_2
2-1-5	4	λ_3
1-2	2	λ_2
2-3	2	λ_3
3-4	2	λ_3
4-5	2	λ_3
1-5	2	λ_1

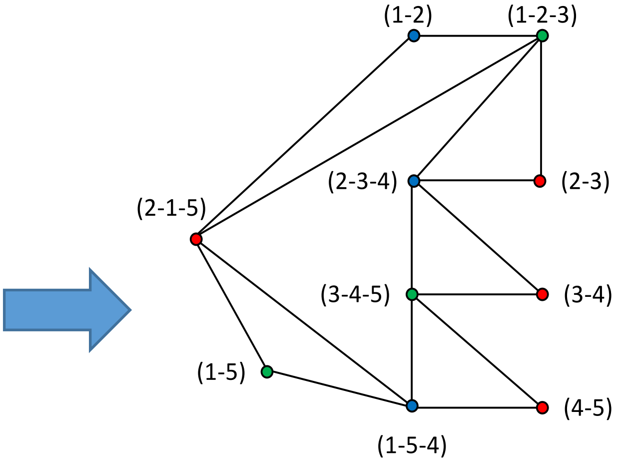


Figure 3.5: Graph *G*(*W*,*P*) with colors assigned: 3 colors indicates 3 wavelengths assigned.

Table 3.1 is obtained from the graph ***G*(*W*,*P*)** of Figure 3.4, considering an ordering strategy based on node degree: the different vertices are sorted in descending order of their degree (*i.e.* Greedy Strategy).

Step (3): The third and final step is to color all nodes of the graph ***G*(*W*,*P*)**, based on the ordering strategy defined in step 2 so that adjacent nodes are assigned different colors. Each color used in the graph corresponds to a different wavelength. The minimum number colors required to coloring all nodes of the graph ***G*(*W*,*P*)** is called chromatic number of the graph and corresponds to the minimum number of wavelengths required to solve the problem of wavelength assignment.

The ordering strategy and node coloring are implemented in Algorithm 3, that uses as input the graph $\boldsymbol{G(W,P)}$. The idea of Algorithm 3 is to number the vertices and then, starting with first vertex ($s(v_1) = 1$) visit the remaining vertices in order, assigning them the lowest-numbered color not yet used for a neighbor [19]. If the nodes are adjacent (v_i and v_j) then different colors must be assigned ($s(v_i) \neq s(v_j)$).

Algorithm 3: Greedy coloring

```
Inputs:
    $G(W,P)$: graph $G$ with edge set $P$, vertex set $W = \{w_1, \dots, w_n\}$;
    $A_v$: adjacency lists;
Outputs:
    Construct a function $f: V \rightarrow N$ such that if the edge $e = (v_i, v_j) \in E$, then
    $s(v_i) \neq s(v_j)$
Data:
    $K$: maximum number of colors; $s(v_i)$ is a set of vertices of graph $G(W,P)$.
set $s(v_i) \leftarrow 0$ for $1 \leq j \leq n$
$s(v_i) \leftarrow 1$
for $2 \leq j \leq n$
    choose a color $K > 0$ for vertex $v_j$ that differs from those of its neighbors
    $s(v_i) \leftarrow \min (K \in N \mid K > 0)$
end
```

In the literature there is an upper bound for the chromatic number [1], [2]. This bound says that if the largest vertex degree in the graph to be colored is D, then it is possible to color the graph $\boldsymbol{G(W,P)}$ using at most $D + 1$ different colors; *i.e.* at most $D + 1$ different wavelengths are needed in the corresponding wavelength assignment problem [1]. In the case of Figure 3.4 the largest vertex degree D is 4, so 5 the is the upper bound value, which is true, since the number of wavelengths obtained with the Greedy Strategy is 3.

3.5.2. First-Fit

In the First-Fit algorithm the wavelengths are indexed, and a lightpath will attempt to select the wavelength with the lowest index. By selecting wavelengths in this manner existing connections will be packed into a smaller number of wavelengths, leaving a larger number of wavelengths available [20]. If the ordering strategy chosen is the Shortest Path First, then a large number of wavelengths will be available to the longest paths.

3.5.3. Most-Used

Most-Used uses the same indexing as the First-Fit. The difference is that it selects the wavelength that is the most used in the network. In this algorithm there is a variable that keep the number of times each wavelength is used per link, that is, the Most-Used algorithm requires a prior knowledge of the state of the network connections. The wavelength that is assigned to the most links is given a higher priority. It has, usually, a better performance than the First-Fit algorithm, since it uses few wavelengths, but, it needs storage and higher computational times than the First-Fit [20].

3.6. Survivability

Optical network survivability translates the ability of a network to continue to offer services in the presence of internal failures, such as link and node failures [21]. In order to minimize these failures there are two paths for each connection, the path that carries traffic during normal operation, known as the working path, and the path that is used when the working path fails, known as the backup path or protection path. The backup path does not have any common links with the working path (*i.e.* disjoint path). In this work we assume that there is a path dedicated only for protection (in the literature it is called 1 + 1 dedicated protection [1]). In order to compute the protection path for each working path, we have implemented the disjoint protection algorithm, shown in Algorithm 4.

Algorithm 4: Disjoint protection algorithm

```
Inputs: netCostM: from the physical topologies (containing costs of all edges)
    s: source node index
    d: destination node index
Outputs: netSurvM: set for the backup paths with and without protection
Create a copy of netCostM matrix, called auxNetCostM
    foreach shortest path, calculated through Algorithm 1 (Dijkstra), in netCostM do
        foreach link in the path do
            remove it from auxNetCostM
    Calculate a backup path, using Algorithm 1 (Dijkstra) with auxNetCostM
    Store the path in netSurvM
Return netSurvM
```

In Algorithm 4 we use the Dijkstra algorithm to compute the working path, and the disjoint path is found by removing the working path from the network and then calculate again the shortest path with the Dijkstra algorithm.

3.7. RWA Application Examples

In this section we use the RWA strategies explained in the previous sections for simple networks in order to test and validate our RWA tool. These RWA strategies were all implemented in MATLAB.

3.7.1. Ring Physical Topology

An optical ring network can consists of ROADMs nodes (with 2 degree) connected as shown in Figure 3.6, in which a 5 node ring network is considered.

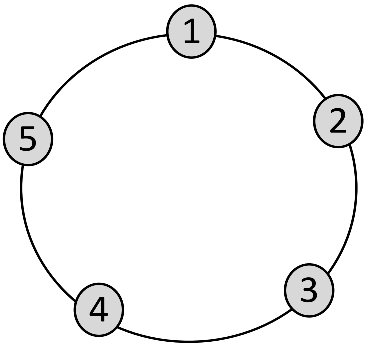


Figure 3.6 : Ring physical topology with 5 ROADM nodes.

Table 3.2: Adjacency matrix of the ring topology of Figure 3.6.

	1	**2**	**3**	**4**	**5**
1	0	1	0	0	1
2	1	0	1	0	0
3	0	1	0	1	0
4	0	0	1	0	1
5	1	0	0	1	0

From the physical topology represented in Figure 3.6 we can obtain the adjacency matrix represented in Table 3.2. Assuming that the cost of each link is 1, which is the same as assuming that the cost of an optical path is given by the number of hops, the cost matrix is the same as the adjacency matrix described in Table 3.2.

Next, consider the traffic matrix given in Table 3.3, which define the logical topology. The traffic matrix is represented in terms of the number of lightpaths. As we can see in Table 3.3 we have a path between each node, *i.e.* a full mesh logical topology. In this scenario after using Dijkstra algorithm to compute the shortest paths (see Figure 3.3) it is possible to determine the number of wavelengths required and the plan of wavelengths using the Graph Coloring, First-Fit and Most-Used algorithms.

Table 3.3: Traffic matrix for the ring topology giving in Figure 3.6.

	1	**2**	**3**	**4**	**5**
1	0	1	1	1	1
2	1	0	1	1	1
3	1	1	0	1	1
4	1	1	1	0	1
5	1	1	1	1	0

Graph Coloring

After calculating all the paths, we need to find the graph $\boldsymbol{G(W,P)}$ and to color the respective vertices (using Algorithm 3) in order to obtain the number of wavelengths. We have obtained the colored graph $\boldsymbol{G(W,P)}$ shown in Figure 3.7 with Algorithm 2 and also using the MATGRAPH tool [22]. With this tool we can use other strategies than the Greedy one implemented with Algorithm 3.

The chromatic number of the graph of Figure 3.7 is 3, using the Greedy Strategy [19]. In this case, as the vertex with the highest degree is $D = 4$, then the upper bound for the chromatic number is 5 ($D + 1$) [1]. With this result we conclude that 5 is actually an upper bound of the real value 3, obtained with the Greedy Strategy.

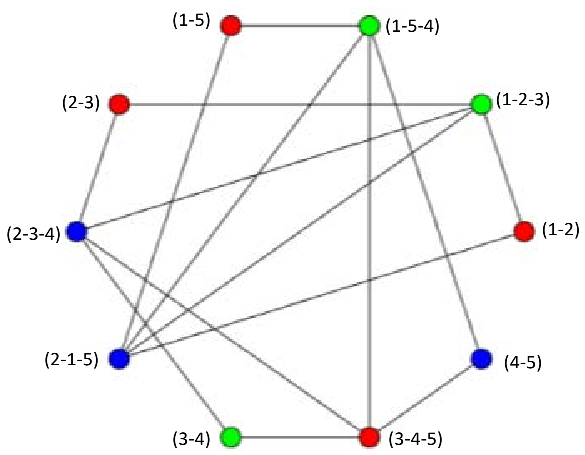


Figure 3.7: Graph Coloring of ring network topology given in Figure 3.6 with a full mesh logical topology.

We have also used the optimal and random strategies (using the MATGRAPH tool) and the number of wavelengths found has a similar value as the one found with the Greedy Strategy.

First-Fit

The First-Fit WA results are shown in Table 3.4 for three ordering strategies: Shortest Path First, Longest Path First and Random Path Order. Traffic matrix considers also a full mesh logical topology with one unit of traffic between all the nodes.

Table 3.4: First-Fit – Ring Network.

Shortest Path First			**Longest Path First**			**Random Path Order**		
Paths	No. of Hops	Wavelength	Paths	No. of Hops	Wavelength	Paths	No. of Hops	Wavelength
1-2	1	λ_1	1-2-3	2	λ_1	3-4	1	λ_1
1-5	1	λ_1	1-5-4	2	λ_1	2-1-5	2	λ_1
2-3	1	λ_1	2-3-4	2	λ_2	1-2-3	2	λ_2
3-4	1	λ_1	2-1-5	2	λ_2	2-3-4	2	λ_3
4-5	1	λ_1	3-4-5	2	λ_3	1-5-4	2	λ_2
1-2-3	2	λ_2	1-2	1	λ_3	3-4-5	2	λ_4
1-5-4	2	λ_2	1-5	1	λ_3	1-2	1	λ_3
2-3-4	2	λ_3	2-3	1	λ_3	1-5	1	λ_3
2-1-5	2	λ_3	3-4	1	λ_1	4-5	1	λ_1
3-4-5	2	λ_4	4-5	1	λ_2	2-3	1	λ_1

Most-Used

The Most-Used WA results are shown in Table 3.5 for the same three ordering strategies: Shortest Path First, Longest Path First and Random Path Order.

Table 3.5: Most-Used – Ring Network.

Shortest Path First			**Longest Path First**			**Random Path Order**		
Paths	No. of Hops	Wavelength	Paths	No. of Hops	Wavelength	Paths	No. of Hops	Wavelength
1-2	1	λ_1	1-2-3	2	λ_1	2-3-4	2	λ_1
1-5	1	λ_1	1-5-4	2	λ_1	1-5-4	2	λ_1
2-3	1	λ_1	2-3-4	2	λ_2	2-1-5	2	λ_2
3-4	1	λ_1	2-1-5	2	λ_2	3-4	1	λ_2
4-5	1	λ_1	3-4-5	2	λ_3	2-3	1	λ_3
1-2-3	2	λ_2	1-2	1	λ_3	1-2	1	λ_1
1-5-4	2	λ_2	1-5	1	λ_3	1-2-3	2	λ_4
2-3-4	2	λ_3	2-3	1	λ_3	1-5	1	λ_3
2-1-5	2	λ_3	3-4	1	λ_1	3-4-5	2	λ_3
3-4-5	2	λ_4	4-5	1	λ_2	4-5	1	λ_4

We can conclude that the number of wavelengths obtained with the Graph Coloring is 3; with the First-Fit is 4 in Shortest Path First, 3 in Longest Path First and 4 in Random Path Order; and with the Most-Used is 4 in shortest path first, 3 in Longest Path First and 4 in random path order.

3.7.2. Mesh Physical Topology

The mesh topology is a topology characterized by having a direct connection between some pairs of nodes (*e.g.* Figure 3.8). In the extreme case of a full mesh network communication is much easier, since any exchange of information between two nodes does not involve the intervention of any other node [23].

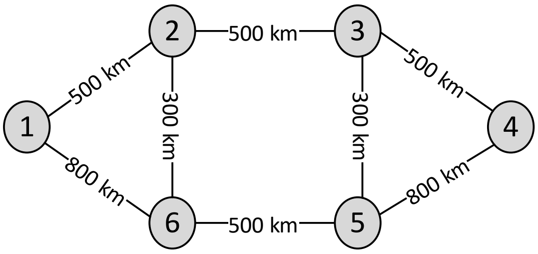


Figure 3.8: Mesh physical topology with six nodes.

Table 3.6: Adjacency matrix of the mesh topology given in Figure 3.8.

	1	2	3	4	5	6
1	0	1	0	0	0	1
2	1	0	1	0	0	1
3	0	1	0	1	1	0
4	0	0	1	0	1	0
5	0	0	1	1	0	1
6	1	1	0	0	1	0

Table 3.7: Cost matrix of the mesh topology given in Figure 3.8.

	1	2	3	4	5	6
1	0	500	0	0	0	800
2	500	0	500	0	0	300
3	0	500	0	500	300	0
4	0	0	500	0	800	0
5	0	0	300	800	0	500
6	800	300	0	0	500	0

From the physical topology given in Figure 3.8 we can obtain the adjacency matrix represented in Table 3.6. Assuming that the cost of each link is the distance in km, the cost matrix can be represented, as shown in Table 3.7. Next, consider the traffic matrix, given in Table 3.8, which defines the logical topology.

Table 3.8: Traffic matrix of the mesh topology given in Figure 3.8.

	1	2	3	4	5	6
1	0	1	1	1	1	1
2	1	0	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	0	1
6	1	1	1	1	1	0

As we can see in Table 3.8 we have a path between each node, *i.e.* a full mesh logical topology. In this scenario after using the Dijkstra algorithm to compute the path it is possible to determine the number of wavelengths required and the plane of wavelengths using again the Graph Coloring, First-Fit and Most-Used algorithms as was done in Subsection 3.7.1 for the ring physical network.

Graph Coloring

The paths for this example, obtained with Dijkstra algorithm, are shown in Table 3.9, considering the shortest path ordering. In this case the metric used is the distance. As we can see the paths 1-6, 1-2-6 have the same distance (800 km). In this situation the tiebreaker criterion used is the path with the least number of hops. In the case in which two paths have the same distance and number of hops, the criterion of tiebreak is, usually, to choose the path that minimizes the load in the most loaded link. However, in our simulator we have implemented a simples rule: we choose the path where the first link has a shorter distance, so when we have to choose between paths 2-3-5 and 2-6-5 we choose 2-6-5 because the path 2-6 (300 km) is shorter than the path 2-3 (500 km).

Table 3.9: Mesh topology paths and respective cost (distance).

Paths	Cost [km]
1-2-3-4	1500
1-6-5	1300
4-5-6	1300
1-2-3	1000
2-3-4	1000
1-6	800
2-6-5	800
3-5-6	800
4-5	800
1-2	500
2-3	500
3-4	500
5-6	500
2-6	300
3-5	300

The colored graph ***G*(*W*, *P*)** is represented in Figure 3.9. The chromatic number of the graph is 5. In this case, as the vertex with the highest degree is $D = 6$, then the upper bound for the chromatic number is 7 ($D + 1$). With this result we conclude that 7 is actually an upper bound of the real value 5 [1]. The Greedy Strategy was used in the graph of Figure 3.9 [19].

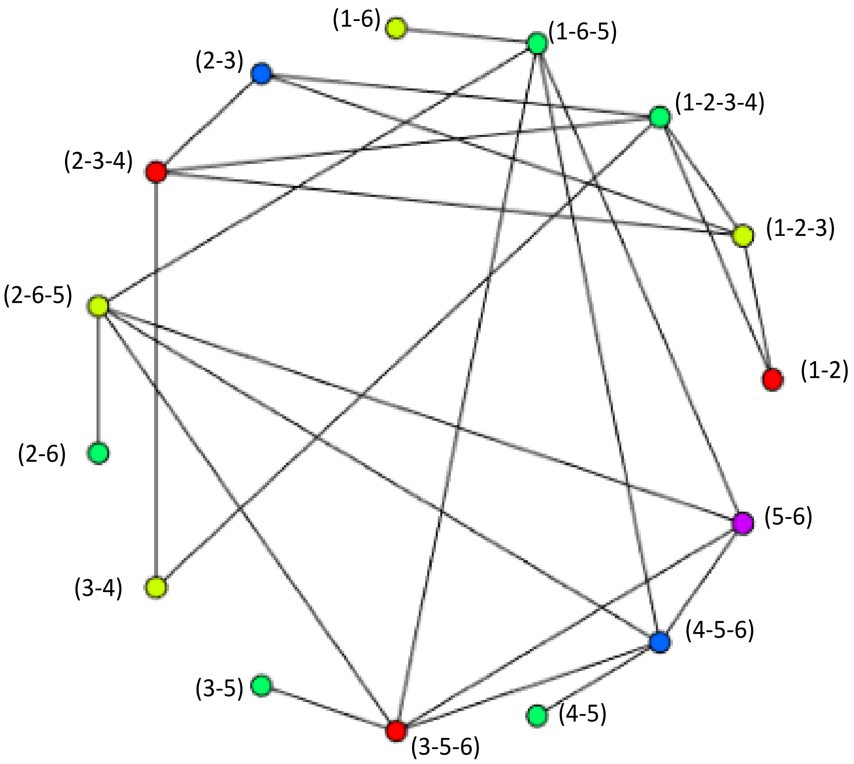


Figure 3.9: Graph Coloring for the mesh physical network topology represented in Figure 3.8 with a full mesh logical topology.

We have also used the optimal and random strategies (using the MATGRAPH tool) and the number of wavelengths found has a similar value as the one found with the Greedy Strategy.

First-Fit

The First-Fit WA results are shown in Table 3.10 for the three ordering strategies: Shortest Path First, Longest Path First and Random Path. Traffic matrix considers also a full mesh logical topology with one unit of traffic between all the nodes.

Table 3.10: First-Fit – Mesh Network.

Shortest Path First			**Longest Path First**			**Random Path**		
Paths	L[km]	Wavelength	Paths	L[km]	Wavelength	Paths	L[km]	Wavelength
2-6	300	λ_1	1-2-3-4	1500	λ_1	4-5	800	λ_1
3-5	300	λ_1	1-6-5	1300	λ_1	4-5-6	1300	λ_2
1-2	500	λ_1	4-5-6	1300	λ_2	1-6	800	λ_1
2-3	500	λ_1	1-2-3	1000	λ_2	2-3-4	1000	λ_1
3-4	500	λ_1	2-3-4	1000	λ_3	5-6	500	λ_1
5-6	500	λ_1	1-6	800	λ_2	1-2-3-4	1500	λ_2
1-6	800	λ_1	2-6-5	800	λ_3	1-2	500	λ_1
2-6-5	800	λ_2	3-5-6	800	λ_4	2-6-5	800	λ_3
3-5-6	800	λ_3	4-5	800	λ_1	3-5-6	800	λ_4
4-5	800	λ_1	1-2	500	λ_3	1-6-5	1300	λ_5
1-2-3	1000	λ_2	2-3	500	λ_4	2-6	300	λ_1
2-3-4	1000	λ_3	3-4	500	λ_2	2-3	500	λ_3
1-6-5	1300	λ_4	5-6	500	λ_5	3-4	500	λ_3
4-5-6	1300	λ_5	2-6	300	λ_1	3-5	300	λ_1
1-2-3-4	1500	λ_4	3-5	300	λ_1	1-2-3	1000	λ_4

As we can observe in Table 3.10, using the strategies Shortest Path First, Longest Path First and Random Path Order we obtain always 5 wavelengths. Figure 3.10 and Figure 3.11 represent the two ordering strategies: Shortest Path First and Longest Path First using the First-Fit WA.

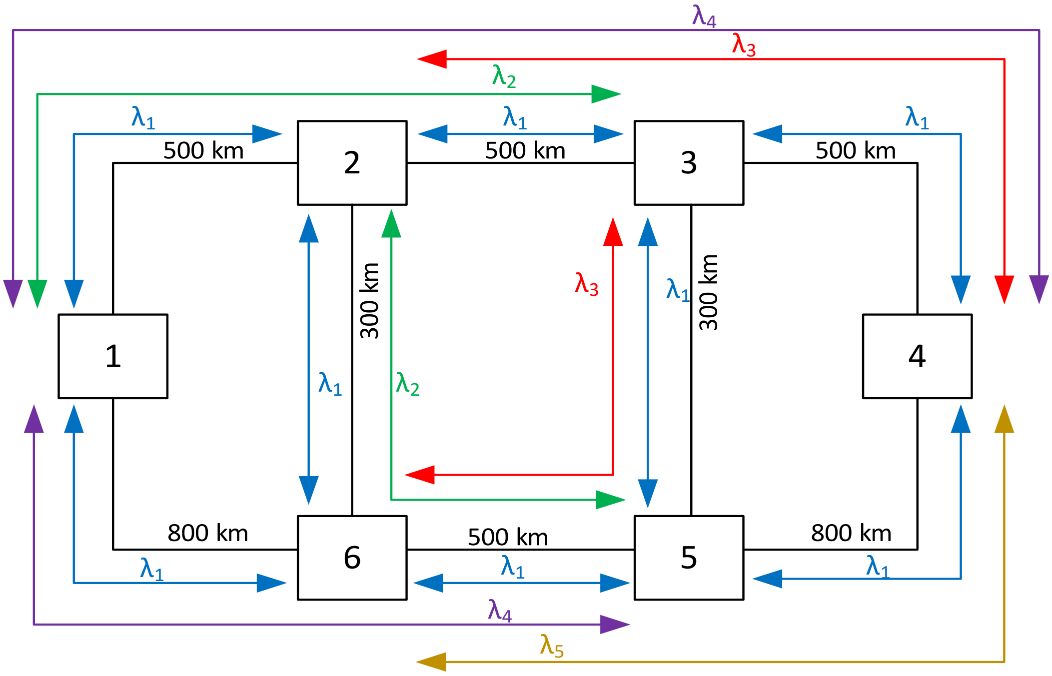


Figure 3.10: Wavelength plan using First-Fit with Shortest Path First Strategy (5 wavelengths are needed).

.

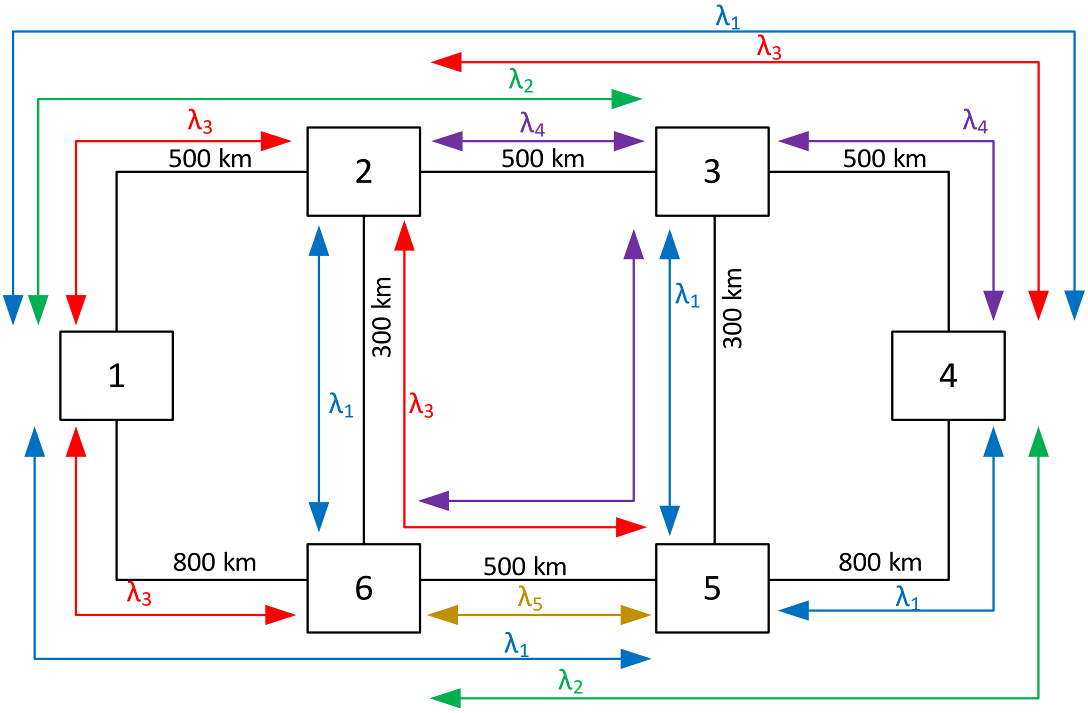


Figure 3.11: Wavelength plan using First-Fit with Longest Path First Strategy (5 wavelengths are needed).

Most-Used

The Most-Used WA results are shown in Table 3.11 for the three ordering strategies. Traffic matrix considers also a full mesh logical topology with one unit of traffic between all the nodes.

Table 3.11: Most-Used – Mesh topology.

Shortest Path First			**Longest Path First**			**Random Path**		
Paths	L[km]	Wavelength	Paths	L[km]	Wavelength	Paths	L[km]	Wavelength
2-6	300	λ_1	1-2-3-4	1500	λ_1	2-3	500	λ_1
3-5	300	λ_1	1-6-5	1300	λ_1	1-2-3-4	1500	λ_2
1-2	500	λ_1	4-5-6	1300	λ_2	3-5	300	λ_1
2-3	500	λ_1	1-2-3	1000	λ_2	2-3-4	1000	λ_3
3-4	500	λ_1	2-3-4	1000	λ_3	4-5-6	1300	λ_1
5-6	500	λ_1	1-6	800	λ_3	2-6-5	800	λ_3
1-6	800	λ_1	2-6-5	800	λ_3	1-6	800	λ_1
2-6-5	800	λ_2	3-5-6	800	λ_4	5-6	500	λ_2
3-5-6	800	λ_3	4-5	800	λ_1	1-2	500	λ_1
4-5	800	λ_1	1-2	500	λ_3	1-2-3	1000	λ_4
1-2-3	1000	λ_3	2-3	500	λ_4	1-6-5	1300	λ_4
2-3-4	1000	λ_2	3-4	500	λ_4	4-5	800	λ_3
1-6-5	1300	λ_4	5-6	500	λ_5	2-6	300	λ_1
4-5-6	1300	λ_5	2-6	300	λ_1	3-4	500	λ_1
1-2-3-4	1500	λ_4	3-5	300	λ_1	3-5-6	800	λ_5

As we can observe in the Table 3.11, using the strategies Shortest Path First, Longest Path First we obtain always 5 wavelengths. Figure 3.12 and Figure 3.13 represent the two ordering strategies: Shortest Path First and Longest Path First using the Most-Used WA.

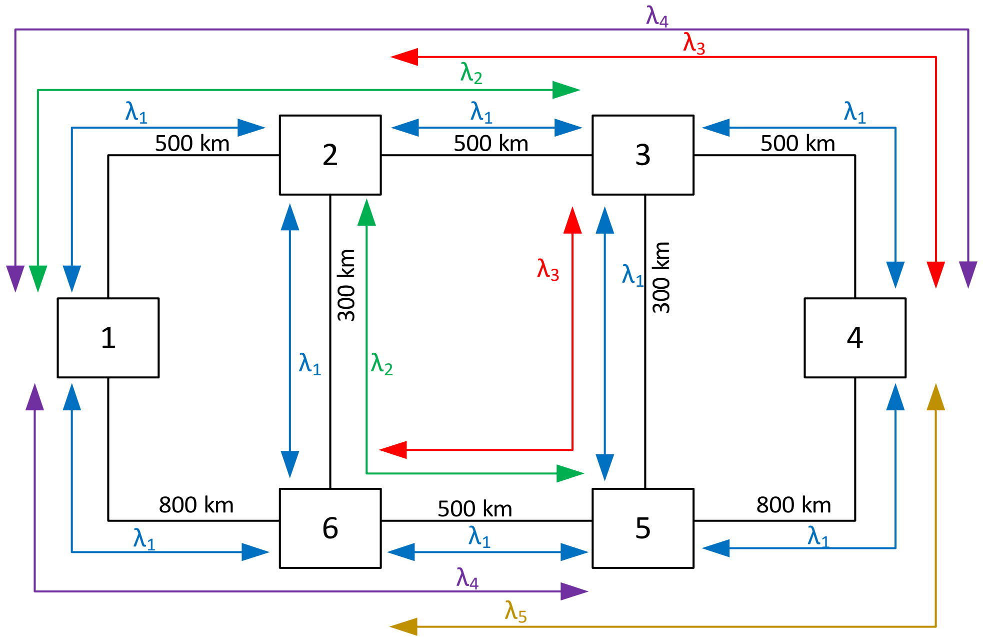


Figure 3.12: Wavelength plan using Most-Used with Shortest Path First Strategy (5 wavelengths are needed).

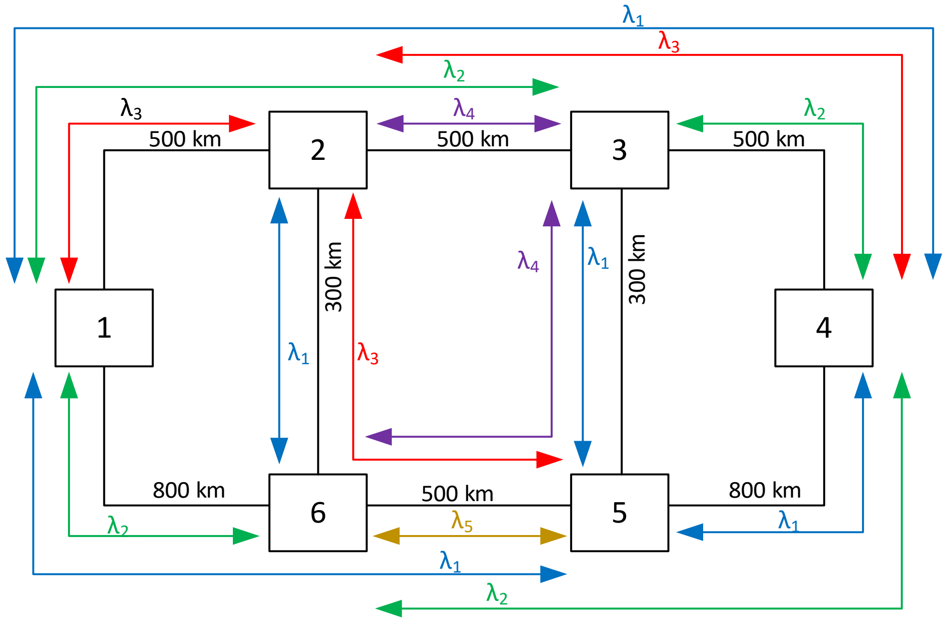


Figure 3.13: Wavelength plan using Most-Used with Longest Path First Strategy (5 wavelengths are needed).

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In these two network examples (ring ang mesh), no differences were observed in the number of assigned wavelengths using both the First-Fit and Most-Used.

3.7.3. RWA with Protection

The mesh topology in Figure 3.8 is used to calculate the working path and protection paths using the Dijkstra shortest path algorithm. These lightpaths are ordered using the strategy Shortest Path First. The First-Fit algorithm is used for the wavelength assignment of each lightpath, as shown in Table 3.12.

As we can see in Table 3.12, there are 15 working paths and these are sorted using the Shortest Path First. For each working path we have calculated a backup path, that must have the same wavelength as the working path. We have concluded that 12 wavelengths are needed for this scenario. Without protection we have calculated only 5 wavelengths (see Figure 3.10). Note that there are three protection paths with a distance equal or greater than 1600 km. Due to noise accumulation, a path with Erbium-Doped Fiber Amplifier (EDFA) has a limit between 1500km and 2500km, so these paths probably could not be established, unless regenerator are used in these particular paths.

Table 3.12: Computation of paths and distance (cost) using Dijkstra algorithm and First-Fit with the Shortest Path First Strategy.

Working Paths	**L [km]**	**Wavelengths**	**Protection Paths**	**L [km]**	**Wavelengths**
[2 6]	300	λ_1	[2 1 6]	1300	λ_1
[3 5]	300	λ_1	[3 4 5]	1300	λ_1
[1 2]	500	λ_2	[1 6 2]	1100	λ_2
[2 3]	500	λ_3	[2 6 5 3]	1100	λ_3
[3 4]	500	λ_2	[3 5 4]	1100	λ_2
[5 6]	500	λ_4	[5 3 2 6]	1100	λ_4
[1 6]	800	λ_5	[1 2 6]	800	λ_5
[2 6 5]	800	λ_6	[2 3 5]	800	λ_6
[3 5 6]	800	λ_7	[3 2 6]	800	λ_7
[4 5]	800	λ_5	[4 3 5]	800	λ_5
[1 2 3]	1000	λ_8	[1 6 5 3]	1600	λ_8
[2 3 4]	1000	λ_9	[2 6 5 4]	1600	λ_9
[1 6 5]	1300	λ_{10}	[1 2 3 5]	1300	λ_{10}
[4 5 6]	1300	λ_{11}	[4 3 2 6]	1300	λ_{11}
[1 2 3 4]	1500	λ_{12}	[1 6 5 4]	2100	λ_{12}

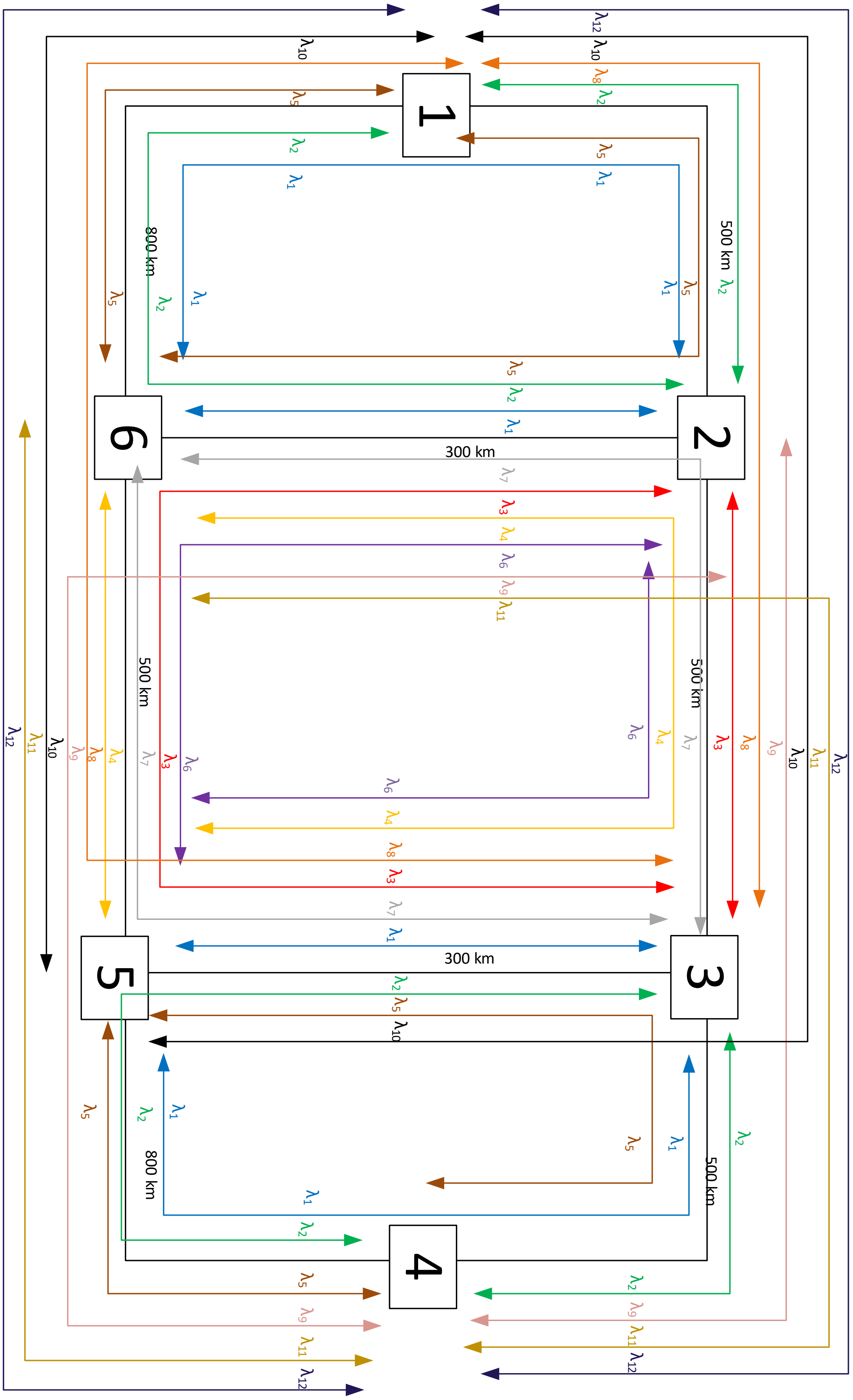

Figure 3.14: Wavelength plan using the First-Fit with Shortest Path First in a protection scenario (12 wavelengths are needed).

Figure 3.14 shows the network mesh topology with the respective working paths and protection paths and with their respective wavelengths.

3.7.4. Comparison Performance

Table 3.13 shows the results obtained in the previous sub-sections for the three wavelengths assignment heuristic strategies: Graph Coloring, First-Fit and Most-Used for the two physical topologies, ring and mesh, and considering the three different ordering schemes.

Table 3.13: Total number of wavelengths calculated by each WA algorithm.

Network	**WA Heuristic**								
	First-Fit			**Most-Used**			**Graph Coloring**		
	SPF	LPF	RP	SPF	LPF	RP	Greedy	Optimal	Random
Ring	4	3	3.5	4	3	3.5	3	3	3.5
Mesh	5	5	5	5	5	5	5	5	5

From Table 3.13, it can be concluded that the total number of wavelengths is almost independent on the WA heuristic algorithm chosen as well as the ordering strategy of the lightpaths for the ring and mesh topologies considered in this section.

3.8. Conclusions

In this chapter we have analyzed and discussed the RWA problem for static networks. The RWA problem was solved with heuristic solutions, for both routing and wavelength assignment (WA). The Dijkstra algorithm was used for routing and for WA the Graph Coloring, First-Fit and Most-Used were used, with more emphasis on Graph Coloring. These algorithms were tested in a small ring and mesh physical topologies and we concluded that in this scenario the number of wavelengths was almost independent of the WA algorithm used, as well as the ordering strategy.

Chapter 4 – RWA Applications Examples to Real Networks

4.1. Introduction

In this chapter we will use the RWA tool developed and tested in chapter 3 in real networks: COST 239 (Ultra-High Capacity Optical Transmission Networks) [24], NSFNET (National Science Foundation Network) [25] and UBN (United States Backbone Network) [26]. First of all, we will introduce, in Section 4.2, each one of these networks. After that we will characterize the physical topology of these networks considering several parameters as described in Section 4.3. In Section 4.4 and 4.5 the RWA tool is used considering the scenarios without protection and with protection, respectively. Finally, in Section 4.6, the conclusions are drawn.

4.2. COST 239, NSFNET and UBN Networks

The networks considered for our simulations are the COST 239, NSFNET and UBN. A brief introduction of these networks will be done in the following paragraphs.

COST 239 – This project started in 1991 for a 5 years period and was extended for a further 2 years. The aim of COST 239 has been, since the beginning, to define criterias which would facilitate the implementation of ultra-long-haul and very high capacity transmission systems with a maximum number of optical nodes [24].

NSFNET - The National Science Foundation Network (NSFNET) was a program of coordinated projects sponsored by the National Science Foundation (NSF) beginning in 1985 to promote advanced research and education networking in the United States. NSFNET was also the name given to several nationwide backbone computer networks that were constructed to support NSF's networking initiatives from 1985 to 1995. Initially created to link researchers to the nation's NSF-funded supercomputing centers, through further public funding and private industry partnerships it developed into a major part of the Internet backbone [25].

UBN – US backbone network is an America network that emerged between 1997 and 1999 to respond to the rapid and massive flow of information through urban areas where lightpath distance requirements vary considerably. As the capacity of the Internet has rapidly increased during the 1990s, each of the traditional media has been incorporated into this new technological framework [26].

4.3. Parameters of the Physical Topology

The physical topology can be characterized by the following parameters:

i) Number of Nodes: represents the total number of nodes in the network;

ii) Number of Links: represents the total number of links in the network;

iii) Total Node Degree: is the sum of all node degrees of the network;

iv) Maximum Cost: represents the maximum cost between adjacent nodes in the network. The cost metric can be the distance or number of hops;

v) Minimum Cost: represents the minimum cost between adjacent nodes in the network;

vi) Average Node Degree: represents the average of the node degree in the network and is given by equation 4.1 [27];

$$< d >= \frac{\sum_{i=1}^{N} d_i}{N} \tag{4.1}$$

where N is the total number of nodes of the network and, d_i is the node degree of node i.

vii) Variance Node Degree: represents the variance of the node degree in the network and is given by equation 4.2 [27].

$$\sigma^2 = \frac{\sum_{i=1}^{N} (d_i - < d >)^2}{N - 1} \tag{4.2}$$

The variance node degree gives a simple measure of the network symmetry – how similar the nodes are in terms of the number of connections.

Next, we present a simple physical topology and evaluate the seven parameters just described. Figure 4.1 represents a simple network with 5 nodes and 6 links. The node degree (d) is represented for each node. The average node degree is 12/5=2.4, and the variance of the node degree is 0.8. The cost metric in this example is the number of hops, so the maximum and minimum cost is the same, one hop.

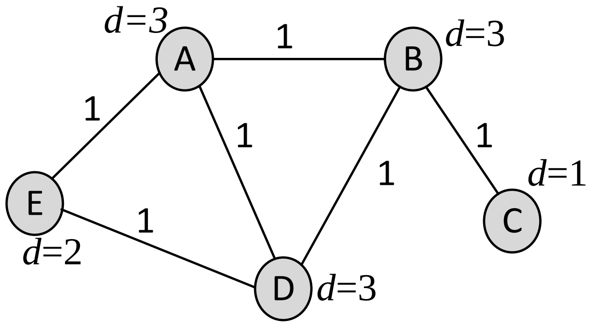

Figure 4.1: Example of a network with 5 nodes and 6 links.

Table 4.1 shows the 7 parameters of the physical network topology represented in Figure 4.1.

Table 4.1: Parameters for the physical topology of Figure 4.1.

Number of Nodes	**Number of Links**	**Total Node Degree**	**Maximum Cost (no. of hops)**	**Minimum Cost (no. of hops)**	**Average Node Degree**	**Variance Node Degree**
5	6	12	1	1	2.4	0.8

In the following sub-sections, we evaluate these 7 parameters for the 3 networks considered – COST 239, NSFNET and UBN. The cost metric in these networks is the distance in km.

4.3.1. COST 239 Network

The COST 239 physical topology is represented in Figure 4.2. Table 4.2 shows the seven parameters defined in the beginning of Section 4.3.

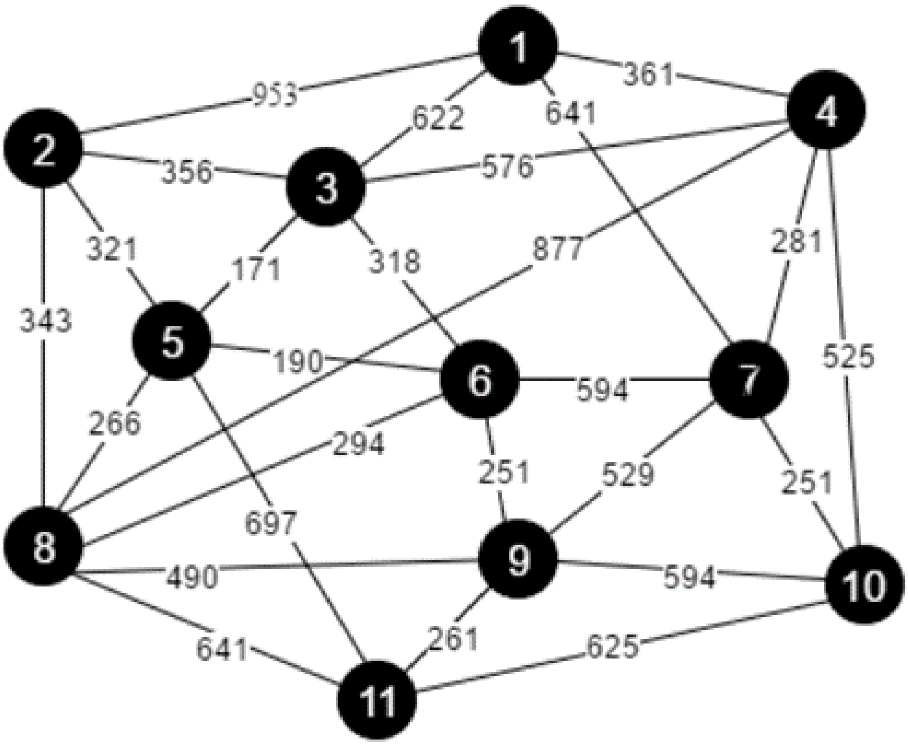

Figure 4.2: Physical topology of the COST 239 network [28].

Table 4.2: COST 239 parameters for the physical topology

Number of Nodes	**Number of Links**	**Total Node Degree**	**Maximum Cost**	**Minimum Cost**	**Average Node Degree**	**Variance Node Degree**
11	26	52	953	171	4.7	0.4

As shown in Figure 4.2, the COST 239 network has 11 nodes and 26 links. The maximum distance between nodes is 953 km and the minimum distance is 171 km. The average node degree is 52/11= 4.7, and the variance of the node degree is 0.4, as shown in Table 4.2.

4.3.2. NSFNET Network

As shown in Figure 4.3, the NSFNET network has 14 nodes and 21 links. The maximum distance between nodes is 2828 km and the minimum distance is 246 km. The average node degree is 42/14=3, and the variance of the node degree is 0.3, as shown in Table 4.3.

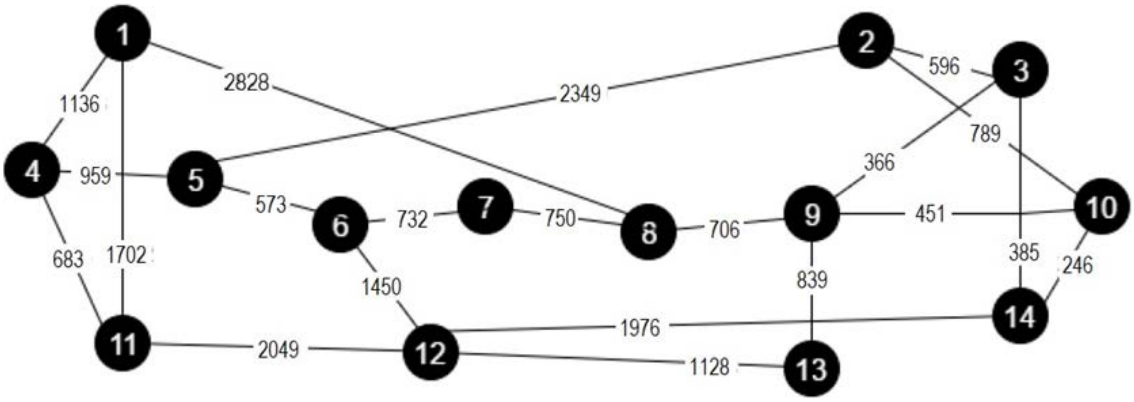

Figure 4.3: Physical topology for NSFNET network [28].

Table 4.3: NSFNET parameters for the physical topology

Number of Nodes	**Number of Links**	**Total Node Degree**	**Maximum Cost**	**Minimum Cost**	**Average Node Degree**	**Variance Node Degree**
14	21	42	2828	246	3	0.3

4.3.3. UBN Network

As shown in Figure 4.4, the UBN network has 24 nodes and 43 links. The maximum distance between nodes 2600 km and the minimum distance is 250 km. The average node degree is 86/24 = 3.58, and the variance of the node degree is 0.9, as shown in Table 4.4.

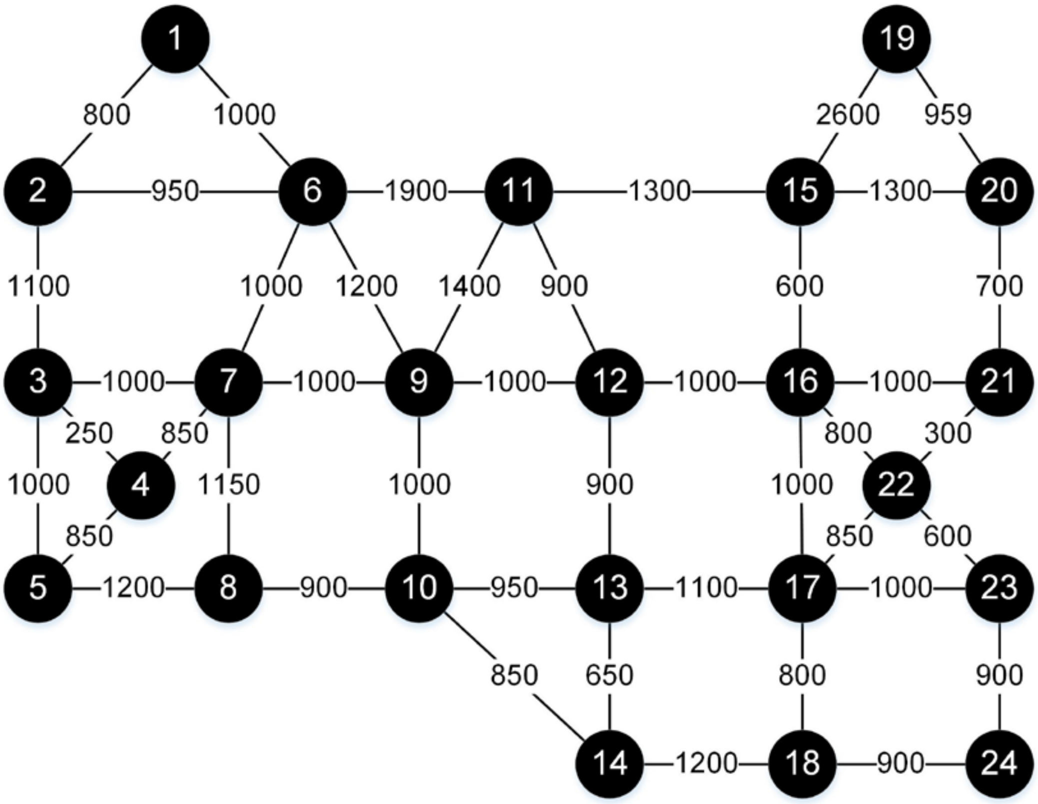

Figure 4.4: Physical topology for UBN network [29], [30].

Table 4.4: UBN parameters for the physical topology

Number of Nodes	Number of Links	Total Node Degree	Maximum Cost	Minimum Cost	Average Node Degree	Variance Node Degree
24	43	86	2600	250	3.58	0.9

By analyzing the results of Table 4.2, Table 4.3 and Table 4.4, we can conclude that the COST 239 network has the highest average node degree (4.7), whereas the UBN network has the highest variance node degree (0.9). Also the UBN is the network with the highest number of nodes, links and total node degree.

4.4. RWA without Protection

In this section the RWA tool developed in chapter 3 is used for planning the COST 239, NSFNET and UBN networks, considering a full logical mesh topology with one unit of traffic in each path.

Table 4.5 shows the total number of wavelengths obtained for each WA heuristics using the three different ordering schemes (SPF, LPF and Random).

Table 4.5: Total number of wavelengths calculated for COST 239, NSFNET and UBN networks.

Network	**WA Heuristic Algorithm**							
	First-Fit			**Most-Used**			**Graph Coloring**	
	SPF	**LPF**	**RP (average)**	**SPF**	**LPF**	**RP (average)**	**Greedy**	**Random**
COST 239	9	9	9	9	10	9.2	9	9
NSFNET	24	24	24	25	24	24,3	24	24
UBN	70	64	66.1	71	64	66.2	64	65.7

From Table 4.5 it can be concluded that the total number of wavelengths used for the same network is almost independent on the WA heuristic algorithm chosen as well as on the ordering schemes of the lightpaths. The only exception appears in the UBN network, since the number of wavelengths obtained with the Graph Coloring algorithm is 64 (Greedy Strategy), whereas with the First-Fit or Most-Used with the SPF Strategy that number is ten percent higher (~70 wavelengths are needed). Note that the Random strategy value, in Table 4.5, represents the average of the number of wavelengths obtained in 100 simulations, and also note that to simulate the optimal strategy in the Graph Coloring scheme the algorithm did not converge.

In order to validate the results of Table 4.5 obtained with the Graph Coloring Algorithm we can use the upper bound that says that it is possible to color the graph using at most D(degree) + 1 different colors, *i.e.* at most $D + 1$ different wavelengths are needed in the corresponding wavelength assignment [1]. For example, the COST 239 topology needs 9 wavelengths, and we have calculated that $D = 15$

(calculated in the MATGRAPH tool), so in this case the upper bound on the chromatic number will be 16 (D + 1). The results obtained with the upper bound and the Greedy Strategy for the NSFNET and UBN are presented in Table 4.6. Note that the value D is obtained from the graph ***G*****(*****W*****,*****P*****)** of the COST 239, NSFNET and UBN (this value was obtained with the MATGRAPH tool).

Table 4.6: Comparison between the upper bound and the Greedy Strategy in the Graph Coloring algorithm for the three networks (COST 239, NSFNET and UBN).

Network	**Greedy Strategy**	**Upper Bound**
COST 239	9	16
NSFNET	24	51
UBN	64	141

We can also validate the results obtained for the UBN network which has 24 nodes and 43 links. For this network we have calculated a variance of 0.9 and a number of wavelengths equal to 70 with the SPF strategy. These results are in agreement with the results obtained by the C. Fenger [31] that considers a network with 30 nodes and 45 links. Figure 4.5 was obtained by C. Fenger (Figure 2(a) of [31]) and we can see that for a variance of the node degree of 0.9 we get around 70 wavelengths.

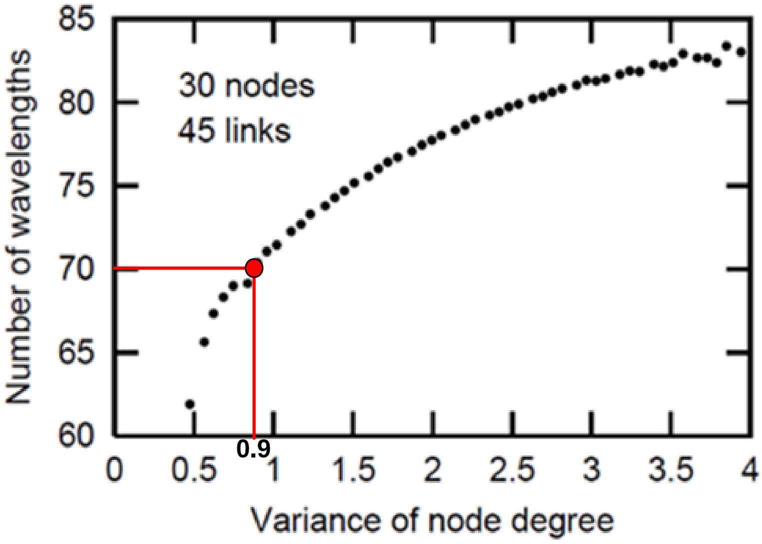

Figure 4.5: Number of wavelengths as a function of the variance of the node degree (Figure 2(a) of [31]).

Finally, we can also say that the results obtained for these 3 networks with the First-Fit and Most-Used algorithms are in accordance with the results reported in [28].

4.5. RWA with Protection

The RWA problem for networks with protection follows the same five sub-problems as that of networks without the protection, as shown in Figure 3.1. For the dedicated protection, used in this dissertation, the same wavelength assigned for the working path is assigned to the backup path.

The RWA with protection is applied to the COST 239, NSFNET and UBN topologies by calculating the working path and protection paths using Dijkstra shortest path algorithm, considering also a full logical mesh topology with one unit of traffic in each path. These lightpaths are ordered using the strategies Shortest Path First, Longest Path First and Random Path Order. The First-Fit and Most-Used algorithms are used for the wavelength assignment of each lightpath.

Table 4.7 summarizes the total number of wavelengths assigned to the scenario without protection and to the scenario with protection.

Table 4.7: Total number of wavelengths assigned without protection and with protection.

Network		**First-Fit**		**Most-Used**	
	Ordering Scheme	Without Protection	With Protection	Without Protection	With Protection
COST 239	ShortestPath First	9	15	9	16
	LongestPath First	9	15	10	16
	RandomPath	9	15	9.2	15
NSFNET	ShortestPath First	24	47	25	48
	LongestPath First	24	46	24	46
	RandomPath	24	46	24.3	46
UBN	ShortestPath First	70	119	71	119
	LongestPath First	64	110	64	110
	RandomPath	64.1	113	66.1	111

From Table 4.7 it can be observed that the number of wavelengths evaluated with protection is almost the double as the number without protection. Once again we conclude that the total number of wavelengths with protection seems to be independent of WA algorithm, as well as the ordering strategy for each individual network.

4.6. Conclusions

In this chapter we applied the RWA tool presented in Chapter 3 in real networks, such as the COST 239, NSFNET and UBN networks. Seven parameters that characterized the physical topology were discussed and it was concluded that the COST 239 network has the highest average node degree (4.7), whereas the UBN has the highest variance node degree (0.9). We have obtained the number of wavelengths needed for the three networks, considering a full logical mesh topology and we have concluded that this number is almost independent of the WA algorithm used as well as the ordering strategy. We validate some of our results, in particular the ones obtained with the Graph Coloring Algorithm by using an upper bound, and the results obtained for the UBN network by comparing our results with the ones obtained by Fenger [31]. Finally, we concluded that the number of wavelengths with protection is almost the double as the same number without protection.

Chapter 5 – Conclusions and Future Work

4.7. Final Conclusions

In this dissertation we have discussed several aspects related to RWA in optical networks for static applications.

In chapter 2 we have introduced the basic concepts of optical networking. We have started by introducing the notion of adjacency, cost and traffic matrix. Then we briefly discussed the optical transport architecture, focusing mainly on the concept of OTU and the optical channel units. Then we have described the ROADM evolution, his components, mainly the WSS, add and drop structures, and their properties (colorless, direnctionless and contentionless), and finally a brief discussion about ROADM architectures, is done.

In chapter 3 we have investigated the RWA problem for static applications. The RWA problem was solved with heuristic solutions, for both routing and WA. The Dijkstra algorithm was used for routing and for WA the Graph Coloring, First-Fit and Most-Used were used and tested. A simulator capable of simulating the Dijkstra routing algorithm and the WA algorithms has been developed. The simulator developed in MATLAB has been tested for small ring and mesh networks, with and without protection and the results are in accordance with our hand calculations.

In chapter 4 we have used our simulator in real networks: COST 239, NSFNET and UBN. Seven networks physical parameters were discussed: number of nodes, number of links, total node degree, maximum cost, minimum cost, average node degree and variance node degree. We have concluded that the number of wavelengths needed for these networks were almost independent of the WA algorithm, as well as the ordering strategy. We have also concluded that when protection is considered almost the double of the wavelengths are needed.

4.8. Future Work

Some topics for future work could be:

1. Consider other logical topologies besides the full mesh.
2. Consider other traffic demands with more than one traffic unit.

3. Consider the OSNR of each path as a cost metric, instead of the distance or the number of hops.
4. Consider other heuristic algorithms for coloring the graph, like the DSATUR algorithm (DSATUR is the abbreviation of degree of saturation), or the Recursive Largest First (RLF) algorithm [2].
5. Consider exact algorithms for the Graph Coloring problem using, for example, Integer Programming (IP) [2].

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