Master of Science in Telecommunication Engineering

***<u>MASTER'S Degree Thesis</u>***

# Spectrum Defragmentation in Elastic Optical Networks


**Advisors**

Prof. Andrea Carena
Prof. Vittorio Curri

**Candidate**

Sk Nasrul Kadir Sunny
s217874

Internship Tutors
TIM-Telecom Italia
Ing. Marco Schiano
Ing. Marco Quagliotti


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Finally, I am thankful to my parents for keeping faith on me and for providing me the courage to fulfill my goal.

# 1 Introduction

The rising popularity of applications on the Internet that require a high transmission capacity, like Video on Demand and others, are expanding the essentiality of the present systems. To meet these requests, a more effective utilization of the optical fiber is required. Elastic Optical Networks (EON) is an innovation that accomplish a more effective utilization of the spectral range, since it sections the spectral resources of the fiber channel, into little, width-consistent spectral slices, called Frequency Slots (FS), that relate to various optical wavelengths, and utilize a proper number of this FS to be served with simply enough data transfer capacity, leaving more spectral resources accessible for future.

Elastic optical networks (EONs) guarantee an effective utilization of the network spectrum resources for traffics above 100Gb/s, where the international telecommunication union telecommunication standardization sector (ITU-T) frequency grid has already fulfilled its limits. In EONs, with the spectrum sliced into different wavelengths, traffic demands are allocated the exact requested bandwidth. The flexibility of EONs offers new features, such as segmentation and aggregation, the settlement of multiple data rates, and elastic variation of allocated resources. The foundation of the lightpath requests in EONs is handled with the routing and spectrum allocation (RSA) problem. In EONs, the optical spectrum reserved for an optical channel is adapted according to the bit rate required by each specific demand. In these kinds of networks, different traffic demand types can be accommodated in one or several frequency slots, if they require several slots larger than the capacity of a single slot unit. The frequency slots assigned to a specific traffic demand must be contiguous, i.e. a demand request can only be satisfied if a sufficient number of free and adjacent slots are available. This is the so-called spectrum contiguity constraint that makes the network design problem more complex and, generally, increases the bandwidth blocking probability.

In this thesis, I have studied the concept and different techniques for spectrum defragmentation in elastic optical networks (EONs). The purpose of this thesis is to study several defragmentation algorithms, methods and techniques. This thesis represents overview of my study by explaining the concept and making comparison between different techniques.

## 1.1 Thesis structure

Chapter 2 introduces overview on the state of the art of optical networks and photonic technologies. It starts with a brief history of the evolution of the optical nodes and networks showing their most significant improvements with each evolutionary stage over the years. Then, it presents a detailed explanation of the fixed grid and flex grid optical systems emphasizing on why the spectrum organization is inefficient in fixed grid. After that, node architecture of reconfigurable optical add-drop multiplexer (ROADM) and functions of dense wavelength division multiplexing (DWDM) considering both multiplexing-demultiplexing. Brief description about functionality of wavelength selective switch (WSS). Finally, the concepts of coherent transmission system.

Chapter 3 introduces brief description of optical networking. It starts with the description of optical fiber link and optical cross connect. Definition and comparison of transparent and translucent network. Then, it presents routing and spectrum allocation or wavelength assignment. Here, it describes several algorithms and their pros and cons. Finally, it describes regenerator placement for wavelength impairment (damage).

Chapter 4 introduces the concept of fragmentation metrics and their use in allocation algorithm. Then it discusses fragmentation problem in optical network considering vertical and horizontal spectrum fragmentation. Finally, it introduces the spectrum allocation algorithms based on fragmentation metrics.

Chapter 5 introduces defragmentation algorithm for elastic optical network. It starts with an overview of defragmentation techniques and working principle of defragmentation algorithm. Then, it continues with classification of fragmentation management techniques where non-defragmentation and fragmentation are being categorized as well as described briefly. Finally, it presents evaluation and comparison of non-defragmentation and defragmentation techniques.

# 2 Overview on the State of the art of optical networks and photonics technologies

Optical networks have been developed in the last years with continuous improvements aimed at increasing flexibility, capacity, reach, and at introducing new functionalities. In this chapter, a brief overview on the evolution on optical networks is presented, together with the concept of Elastic Optical Networks (EONs) and its advantages with respect to fixed grid Wavelength Division Multiplexing (WDM) networks. The chapter ends with the rigorous explanation of the spectrum fragmentation issue, and why it affects more EONs than the traditional fixed grid networks.

Driven by the increasing growth of network traffic, efficient utilization of spectral resource has become a key milestone in elastic optical networks. Unlike traditional WDM networks, which make use of rigid spectral grid allocation, EON have the potential to achieve higher spectrum utilization by assigning spectrum slices proportionally to the amount of traffic carried by each demand.

In recent times there is much research focused on this technology, as this could lead an enormous impact on performance and boost the expansion of optical networks soon.

## *2.1 Evolution of optical network systems*

The first commercial optical transmission system deployed in 1980 had a line rate of 45 Mb/s, it was a single wavelength system made up of a transmitter, a fiber line, and a receiver. About fifteen years later WDM systems have become an industrial reality and this fact brought additional capacity and scalability to optical communication systems. In fiber-optic communications, wavelength division multiplexing (WDM) is a technology which multiplexes several optical carrier signals onto a single optical fiber by using different wavelengths of laser light. Before the introduction of WDM only a single optical channel was carried in an optical fiber, with the modern technology it was possible to transmit data using a wide portion of the available optical spectrum, because it is divided into many non-overlapping wavelengths, with each wavelength supporting a single communication channel.

The commercial deployment of point to point WDM transmission systems came in 1995, which included only eight channels at 2.5 Gbit/s, nevertheless, to stay ahead of perceived demand, in 1997 systems of 16 wavelength with a total capacity of 40 Gb/s were deployed.
New components were required for the new WDM technology: it was necessary to amplify optical signals at intermediate points to compensate for the attenuation introduced by the optical fiber and WDM filters, additionally; a way to add/drop individual wavelengths was required.
In the early 90's, the development of Erbium Doped Fiber Amplifier (EDFA) was one of the key enablers of WDM networks because direct amplification of the optical signal prevented the use of many expensive optoelectronic regenerators on long haul systems. The optical fiber amplifier can amplify several optical signals at the same time, avoiding conversion into the electrical domain. EDFAs also proved cost effective in point to point links as they extended the achievable reach without regeneration. The optical gain achieved with EDFA is sufficient to compensate for loss of a 100km long optical fiber span which made the EDFA an ideal amplifier for long haul WDM transmission systems. The parallel Optical add / drop multiplexers (OADMs) were developed, they allowed to build optical networks mainly limited to ring topologies, with OADMs to add/drop wavelengths at each node, that made possible to connect one node to many other nodes using the same optical fiber by selecting different transmission wavelengths for different demands.

The following revolutionary step was the development of optical switches called Optical Cross Connect (OXC): they were created with the objective of implementing mesh networks with the switching function directly implemented in the optical domain. These switches had a large switching matrix to switch each individual wavelength from one of N input fiber to any of N output fiber. OXC allowed building the earlier Wavelength Routed Network (WRN). The optically routed networks have some major advantages with respect to the so called opaque networks implemented by electrical cross-connect: the elimination of optical-electrical-optical (OEO) conversion in network nodes which is expensive and power-consuming. The problem at that time was the substantial number of ports of OXC: one for each wavelength and direction. Optical nodes were required to switch large numbers of wavelengths. As an example, 80 wavelengths in the C-band, from several fibers, this brought the developments of the Multi-Granular optical cross connect (MG-OXC). MG-OXCs reduce the cost and complexity of OXCs by grouping wavelengths together into bands and switching them using single cross connections.

Meanwhile, the major concerns in the realization of optical communication systems were the coarse allocation and the large granularity of the wavelength. Reconfigurable OADMs (ROADM) were proposed, which made possible the adding of remotely reconfigurability to select, which wavelength are added/dropped at an optical node without needing to replace the hardware every time. Then with the arrival of Wavelength Selective Switches (WSS), independent mux/demux and switching devices were not required, because WSSs provide both filtering and switching functions. WSS-based ROADMs may have multiple degrees, instead of only two, which makes ROADMs usable for the realization of mesh networks. With the introduction of polarization division multiplexing, phase and amplitude modulation formats, coherent detection and digital equalization in electrical domain along with the advancement in optical amplification enabled long-distance dense wavelength-division multiplexed (DWDM) transmission with per-channel bandwidth of 100 Gb/s.

## *2.2 ROADM node architecture*

In Optical Communication, a reconfigurable optical add-drop multiplexer (ROADM) is a form of optical add-drop multiplexer that adds the ability to remotely switch traffic in a WDM system at the wavelength layer. This is achieved using a wavelength selective switching module. This allows individual or multiple wavelengths carrying data channels to be added and/or dropped from a transport fiber without the need to convert the signals on all the WDM channels to electronic signals and back again to optical signals. ROADM functionality originally appeared in long-haul dense wavelength division multiplexing (DWDM) equipment, but by 2005, it began to appear in metro optical systems because of the need to build out major metropolitan networks to deal with the increasing traffic packet-based services. The switching or reconfiguration functions of a ROADM can be achieved using a variety of switching technologies including Microelectromechanical systems (MEMS) liquid crystal, thermo optic and beam-steering switches in planar waveguide circuits, and tunable optical filter technology. In the following section, more elaborate description is available regarding basic architecture of ROADM, wavelength selective switch (WSS), ADD/DROP architecture and Flex ROADM.

### 2.2.1 Basic Architecture

When DWDM technology was introduced in optical transport networks, its main function was to provide capacity enhancement so that a fiber could carry more synchronous optical network (SONET) or synchronous digital hierarchy (SDH) channels. Although the SONET/SDH network has mainly a ring structure, DWDM was used as a point-to-point topology between nodes so that many SONET/SDH rings could share a fiber. The only function needed was wavelength multiplexing and demultiplexing at each node. Figure 1 shows an example of point-to-point multiplexing and demultiplexing where four nodes are connected by four linear DWDM segments to form a ring. To add flexibility, DWDM networks evolved into multi node linear and ring configurations. When a wavelength reached a node, it could be designated to either stop at the node or pass through the node. The channels that pass through the node are referred to as express channels. In addition, wavelengths could be added into the DWDM stream at intermediate nodes. This introduced the concept of wavelength add/drop in nodes that are referred to as optical add/drop multiplexers or OADMs.

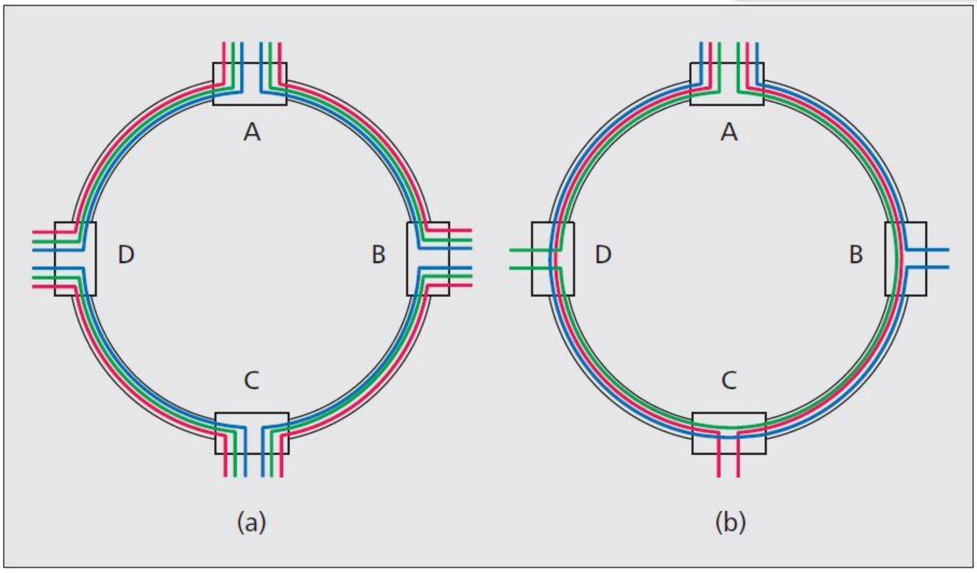



Figure 1- DWDM functions (a)multiplexing/demultiplexing (b) add/drop. [2]

With the wavelength add/drop function, wavelengths could now be added and dropped in pre-planned network configurations. The channel add/drop function, however, is static, and generally required manual reconfiguration to modify channel add/drop locations.

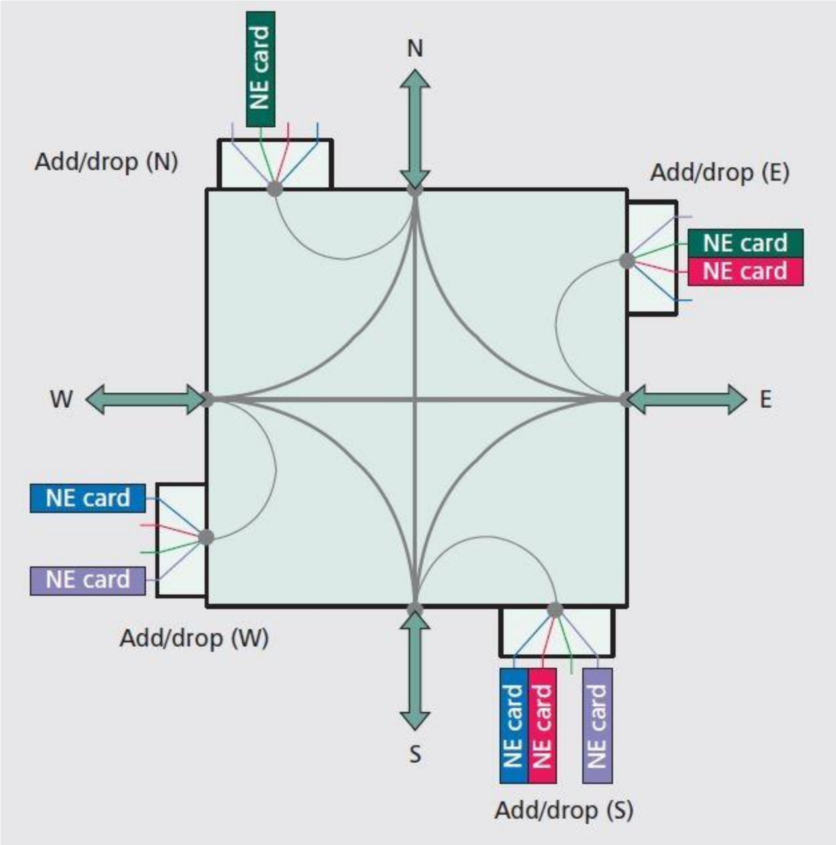



Figure 2 : Architectures of basic ROADM designs. [2]

An optical splitter distributes the optical power from the input port (on the left side of the diagram) to the output ports on the right Figure 2. The power splitting ratio along the output ports is device-dependent. The power splitting ratio is generally designed to be wavelength-independent over the operating frequency range of the OADM. A 1 × 2 fiber coupler is a typical optical splitter and splitting ratios such as 50/50 or 90/10 are common. When a splitter is used in the opposite direction, it becomes an optical coupler. The power loss between a pair of input ports and output ports remains the same in both the splitter and coupler configurations. An N × N optical coupler is an expanded version of a 1 × N optical coupler. For an N × N coupler, the input power at any port on one side of the device is distributed into all ports on the other side of the device with a certain distribution ratio. A wavelength splitter (also referred to as a wavelength multiplexer/demultiplexer) is a device to separate optical channels with different wavelengths, or different "colors," with minimal loss through the device. A wavelength splitter can operate to combine or separate wavelengths to perform wavelength multiplexing and demultiplexing functions. The channel separation is normally distributed evenly along optical frequency. For example, the channel separation or channel spacing, can be 50 or 100 GHz. Since a wavelength splitter is a passive device, the wavelength or wavelengths assigned to each port are fixed. A photonic switch is also a useful building block for ROADM designs. The photonic switch provides pure optical signal routing with no conversion of the signal into the electrical domain. A photonic switch may have small port counts, such as 1 × 2 or 2 × 2. Various technologies, such as mechanical beam steering, polarization rotation, or interference, can be used to build photonic switches. Photonic switches with large port counts are also useful for ROADM designs. For example, a 320 × 320 photonic switches with multiple wavelength splitters can provide a flexible add/drop structure for a ROADM node.

Considering broadcasting and selecting network without routing, information from a source is broadcasted to all receivers; receivers select the information directed to them and discard the rest. All nodes have visibility on all network traffic, but do not need to process (switch) all of it. The aim is to limit the bandwidth processed by network nodes, finding the proper balance between photonic and electronic technology. Each node is usually attached to two fibers: one to transmit, one to receive. WDM channels are available. TX and Rx operate on a single WDM channel at a time (to reduce electronic bandwidth). It is possible to observe collisions and contention – Collision: two or more transmitters transmit on the same channel at the same time – Contention: a single receiver must tune to two or more channels at the same time. We need a Medium Access Control (MAC) protocol. Nodes can be equipped with one or more TX and RX devices, which may be tunable or fixed. Tunable TXs and RXs are more expensive (and tunable rxs usually cost more than tunable txs). Connectivity may be limited due to components' or complexity constraints. For example, if node i has a fixed tx on λi and a fixed rx on λ|i-1|N, a ring logical topology results. Traffic will be then routed using multi-hop paths, going through many intermediate nodes, where OEO conversion is performed. Different resource allocation strategies can be adopted when the traffic pattern is relatively stable (flow duration much larger than propagation delays), or when a dynamic, packet by packet, network control is necessary. Often time is slotted, and statistical time multiplexing is adopted. Tuning time of tx/rx may be a non-negligible and must be taken into proper account. One (or more) channel can be devoted to signaling (almost necessary in broadcast stars). Slot synchronization does not come for free, since the slot time is small (guard times must be insignificant compared to the slot duration). Bit synchronization must be faced as always.

### 2.2.2 Wavelength Selective Switch (WSS)

THE wavelength-selective switch (WSS) has undergone significant development recently to address reconfigurable optical add/drop multiplexer (ROADM) applications in multiwavelength optical networks. The ROADM is a relatively new commercial application that allows software-controlled transparent optical switching of wavelength channels into and out of a fiber in an optical network. The ROADM application is particularly valuable because denser wavelength-division multiplexing (DWDM) networks are deployed extensively in metropolitan networks, which have many wavelengths and a bandwidth demand that is relatively large and unpredictable even with sophisticated network planning [1]. The ROADM is valuable in this type of network by adding the flexibility in software to "express" individual channels through a node or to "add" and "drop" a wavelength for information access or rerouting along another path in the network. Basically, the wavelength selective switch is at the heart of current-generation ROADM networks and, similarly, has a significant role to play in next generation ROADM networks. The benefits of WSS switches are that the technology is widely deployed and well understood by network operators around the world. Today, there are several variants of WSSs commercially available for different applications from edge to metro to core, including 1x2, 1x4, and 1x9 WSS variants. New WSS modules are coming to market for next-generation networks and applications.

The WSS has become the most widely used optical switch for this application, because it is a very cost-effective and scalable technology, which is also among the most flexible solutions from an optical networking perspective. Early concepts of a wavelength-based fiber-optic switch integrated a digital Microelectromechanical systems (MEMS) technology into a fiber optic spectrometer [1]. This was extended to 2-D MEMS mirrors and started commercial development about ten years ago, using digital MEMS, analog MEMS, and liquid crystal (LC) switching technologies. The first optical networking system with WSS-based ROADM functionality integrated in the system used two-port LC-based wavelength blockers and an eight-port analog MEMS -based system. It is probably not unusual that initial demonstrations of the WSS and ROADM applications used such a wide range of technologies; however, it is unusual that after ten years of commercial development, all these technologies continue to have commercial success in this sector. the WSS is a compact micro optics device, which is compared with equivalent functionality, the WSS allows approximately half the size, half the cost, and about half the insertion loss over the discrete architecture.

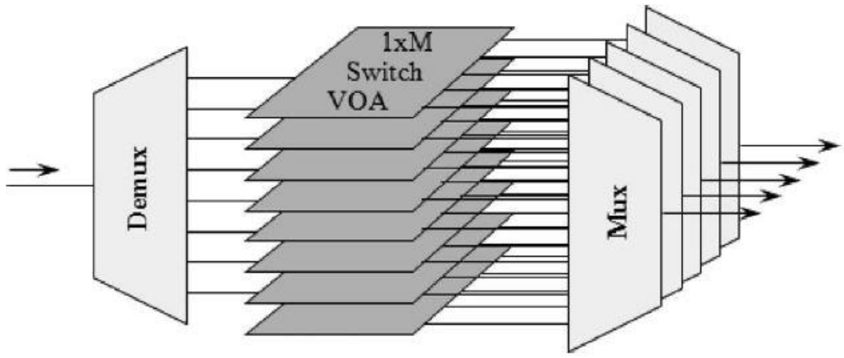



Figure 3: Functionality of a WSS; it separates N wavelengths into independent switching elements for independent, nonblocking switching, and Variable optical attenuator (VOA) control to any output. [1]

In addition, there are multiple switching and filtering performance advantages of free-space integration, and these will be addressed in the performance section. The integrated functionality of the WSS is central to the future of ROADM networks because the functions, as shown in Figure 3, are quite valuable in this networking application. The most common WSS architecture for building the ROADM switch, which is presented in Figure 4.

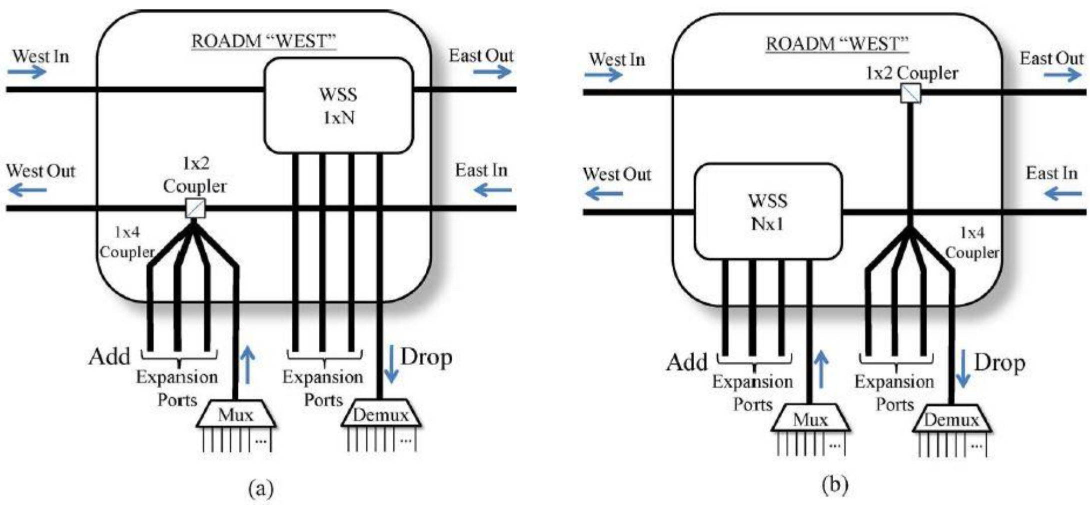



Figure 4: Most common optical switching arrangements in a ROADM network element for (a) a filtered drop configuration where the WSS is positioned to drop optical signals, and (b) a

filtered add configuration where the WSS is positioned to add signals to the optical network. [1]

There are several common features of both architectures.

- The availability of extra “expansion” ports for adding and dropping many wavelengths in a single fiber. These are primarily reserved for creating extra “degrees” wavelength interconnection of a mesh network, such as “north” and “south.” The value of these devices in building cross connects and mesh optical networks is described in detail elsewhere, but the functionality of the WSS is the only current ROADM solution that enables this flexibility.
- The use of only one WSS as a wavelength filtering element on the “express” optical path through the ROADM. This limits the accumulation of transmission penalties from undesirable “filter narrowing,” which ultimately limits the number of ROADM elements and the per channel bandwidth of the system.
- The use of a Mux/Demux to create cost-effective extra ports for ingress (Add) and egress (Drop) of individual wavelengths from the network. This arrangement nicely segments WSS ports, which have high optical performance and are relatively expensive, and uses them for the “express” paths in the network that a signal may experience ten or more times. Conversely, the Mux and Demux filtering is much less sensitive to optical performance because a given signal only sees these elements at the ingress and egress of the network. This allows reduced optical filtering performance to accommodate a device that instead provides a minimum cost/port. Note this Mux and Demux element could be a conventional Mux with fixed wavelength-port mapping; however, there is strong interest to use “colorless” WSS devices or tunable filter array devices here that drop any wavelength with fewer ports and are capable of adjusting wavelength or direction of the network connection to facilitate restoration [1]. While the two arrangements in Figure 4 have many similarities, the different configurations can leverage the functionality of the WSS to differentiate the network level functionality. For example, the filtered drop arrangement in Figure 4 (a) is a more secure network because access to drop signals is controlled by the WSS. This can be important when some wavelengths in a network are only intended to be accessible at certain network locations. Typically, this architecture is preferred in applications with a limited number of add channels, where it may be possible to eliminate all spectral filtering on the add path and use a very inexpensive passive coupler as a “colorless” multiplexer. This

become less attractive for a large (>4) number of channels because of the noise impact of the passive loss in the add path, and because the passive multiplexer enables additive noise funneling from each of the add sources into the ROADM network. The filtered add configuration in Figure 4 (b) is advantageous because all add channels in the network have VOA power level control from the WSS as they enter the network. The largest power level uncertainty in a transparent optical network is for the add channels; therefore, if this can be corrected and optimized before the signal enters the first optical span, this creates a significant optical SNR advantage in the system. In addition, the position of a passive coupler to drop all wavelengths entering the ROADM allows for a built-in optical broadcast of all channels. This can be used, for example, in video distribution optical layer protection.

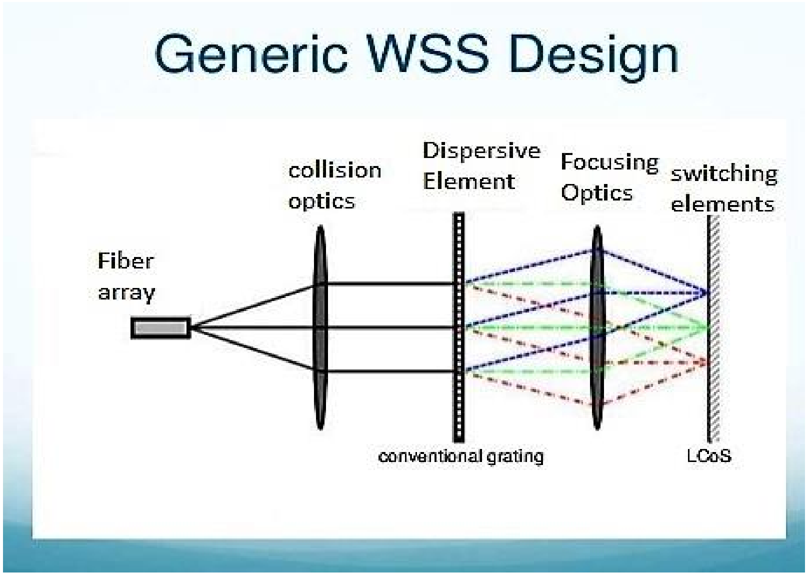



Figure 5 : Schematic of generic WSS.

The WSS technologies prevalent in current networks all use conceptually similar free-space optical designs. These designs all have the following.

- DWDM Fiber input launching the light into free space;
- Diffractive grating to spatially separate the incoming channels;
- Optical switching array capable of redirecting the wavelengths incident on different parts of the array toward different output ports;
- Diffractive grating to recombine the channels onto individual output ports;
- Fiber coupling system to collect the light for each of the output fibers.

While this description and the arrangement in Figure 3 describe a WSS as a 1 × N switch, all designs can be configured to operate in either direction (1 × N or N × 1, as shown in Figure 3), and some designs are fully reciprocal such that a single device can operate in either mode. The performance and functionality differences of different WSS technologies are almost exclusively derived from the differences in switching technology in item 3 mentioned earlier. While all commercial WSS devices are not characterized by only one classification, there are four general classifications defined by two characteristics of the optical switch. The first characteristic is the switching actuation technology, which in commercial devices is either MEMS (Micro-Electro-Mechanical-System) or LC, and the second characteristic is the number of pixels (switching elements) used to direct a single channel (i.e., a single pixel/channel or multipixel/channel). Among many potential classifications, this system is useful because it defines some fundamental characteristics of the constituent devices for relative comparisons. The following are brief descriptions of each of the classes.

In colorless/directionless applications, a WSS port is used for every wavelength that is added/dropped (independent of which degree of the node it is associated). Therefore, higher port count WSSs are advantageous as they improve the cost per port, as well as increase the number of add/drop ports supported by a WSS module. Also, with the total number of colorless and directionless add/drop ports serving a node determined by the number of high port count WSS modules, the total number of ports can be incrementally increased over time as the traffic requirements increase simply by adding additional modules. This allows operators to flexibly scale both node equipment and costs according to the unpredictable network growth with lower upfront costs. Finally, the modularity of add/drop ports allows for cost efficient architectures with separate modules to support the isolation of working and protect wavelength pairs. Thus, we see a trend toward WSSs with port counts beyond nine and toward 20 or above.
There is some desire for future support of an M × N nonblocking WSS switch as a “Contentionless” device. Such a device would be extremely useful to route traffic from M inputs to N outputs while avoiding wavelength contention. This function is valuable in complex mesh optical networks.

### 2.2.3 ADD/DROP architecture

As the optical reach of systems was extended and the number of wavelengths supported per fiber increased, it became possible for some wavelengths channels to optically bypass some nodes to both simplify the node and eliminate opto- electronic termination equipment which was previously required to allow traffic to bypass node. To enable this, wavelength optical add/drop multiplexer (OADMs) were introduced in ring or liner chains. Today, network operators are simultaneously faced with escalating bandwidth requirements, less predictable and more dynamic traffic topologies. Therefore, many operators have turned to reconfigurable optical add/drop multiplexer (ROADM) technology to provide an optical network infrastructure over which they can flexibly deploy wavelengths generally between any pair of nodes.
Considering wavelengths flexibility into the network, wavelength can reach any adjacent node in the network through switching function. So, the network is mesh-network and each node in the network behaves like junction point rather than stopping point. Thus, introduction of degree ROADM networks, each degree represents a direction between two nodes. A degree is another term for a switching direction and is generally associated with a transmission fiber pair. Multi degree ROADM introduce three more services like colorless, directionless and Contentionless. Colorless service can be defined when wavelengths can be set under control and not fixed by physical add/drop port on ROADM. When wavelengths can be added or dropped from any direction (under software control), the implementation is referred to as directionless. Contentionless architecture allows multiple copies of the same wavelengths on a single add/drop structure.

Considering the common building blocks for ROADM, the common devices are optical splitter or coupler, wavelength splitter or coupler, tunable filter, wavelength selective switch and photonic switch. Optical splitter or coupler distributes the optical power from the input port to the output ports. A wavelength splitter (also referred to as a wavelength multiplexer/demultiplexer) is a device that separates optical channels with different wavelengths, with minimal loss through the device. A tunable filter is a device that allows a wavelength or a range of wavelengths to pass through but blocks all other wavelengths. A wavelength selective switch (WSS) is a device that can switch a selected wavelength or wavelengths from an input port to an output port. The photonic switch provides pure optical signal routing with no conversion of the signal into the electrical domain. In a basic ROADM design, channels are routed to the wavelength add/drop structure. This is accomplished by using an optical splitter, wavelength splitter, and WSS. The optical splitter distributes incoming channels from one degree to the add/drop portion of this degree and to the WSSs of all other degrees. A wavelength splitter separates the channels to the drop ports. To add channels, an optical coupler combines channels and sends the channels to a port on the WSS. In applications where many channels are added, the optical coupler is replaced with a wavelength coupler to reduce loss.

Basic multi degree ROADM node architecture, which is subject to the constraints of color and direction at each add/drop port. In each degree, an array waveguide grating (AWG) is connected to one of the optical splitter ports is employed to filter each drop wavelength, and a WSS is used to combine add and bypass signals. The multi degrees are internally connected by fibers. Such a fiber connecting configuration internally ensures non-blocking between the nodal degrees. The architecture is colored due to the color constraint of each AWG port. It is directional because each add/drop port is dedicated to a nodal degree.
Colorless means that each add/drop port of a ROADM node should not be wavelength selective; any wavelength can be added/dropped at any port. Colorless feature at a local add/drop port - ability of tunable transponders to have wavelength transparent access to all the DWDM network ports. In a colorless design, any wavelength can be assigned to an add/drop port. Previously, the wavelength splitter limited each drop port to only one wavelength. To reconfigure a services wavelength color, the receiver must be moved to the port with the corresponding drop color. To eliminate this constraint, a WSS can be used to replace the wavelength splitter and provide the colorless functionality. In transmitter side does not need to be changed since each transmitter sends out only one wavelength, and the optical coupler do not consider the color. When combining channels with a coupler, crosstalk between different channels can be an issue. Designs may need to specify the suppression ratio in laser mode or filter the signal to reduce its bandwidth (and filter out noise) before the colorless combining is performed. Also, with this implementation software must protect the system from an incorrect wavelength assignment that interferes with a preexisting channel of the same wavelength.

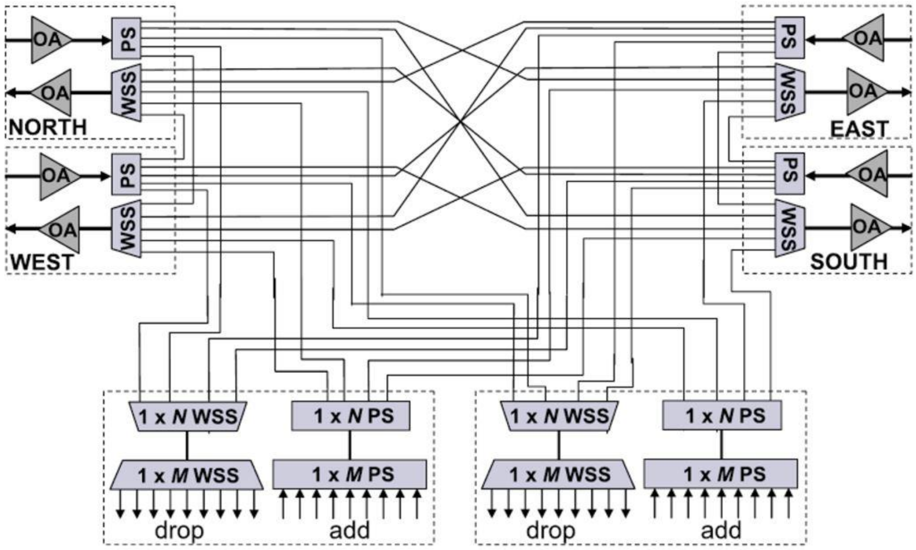



Figure 6: colorless and directionless add/drop architecture. [3]

Directionless means that an add/drop port at a node is not nodal degree selective; any channel added on a port can be directed to any outbound nodal degree, and vice versa. Directionless feature at a local add/drop port - ability of tunable transponders to have non-blocking access to all the DWDM network ports. A directionless add/drop structure provides the freedom to direct a channel to any degree of the ROADM and is implemented by connecting an add/drop structure to every degree on the ROADM. This can be realized by adding another 1 × M optical coupler to the add structure and another 1 × M WSS to the drop structure. As, it is shown in Figure 6 . With this modification, a separate add/drop structure no longer needs to be associated with each degree of the node. As the number of components increases in colorless and directionless designs, optical amplification will be required in the add/drop structure for most practical implementations to overcome component loss.

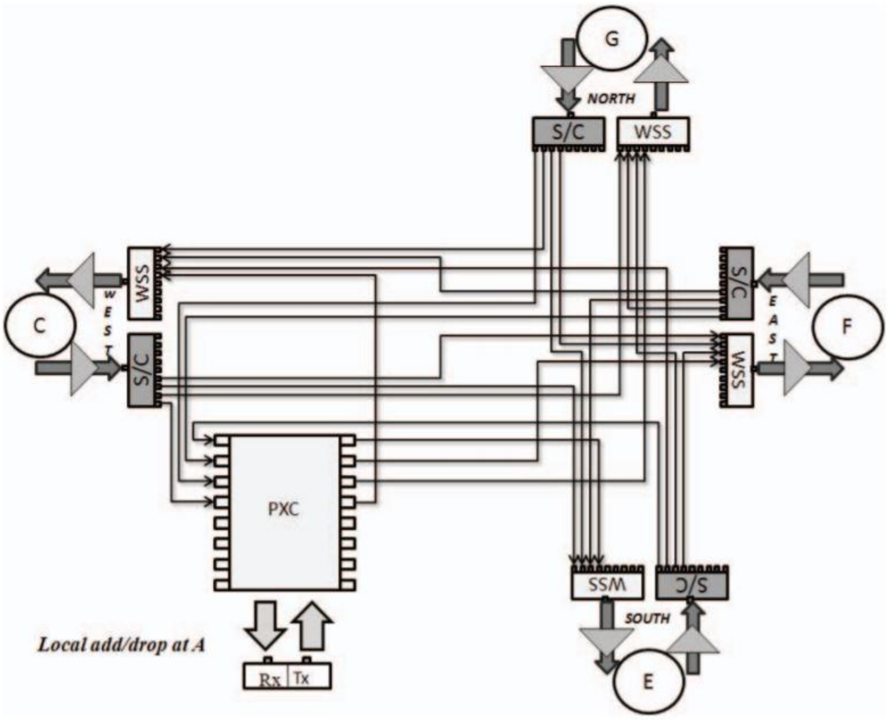



Figure 7 : Colorless, Directionless and Contentionless 4 Degree ROADM structure. [6]

Contentionless means that, within the ROADM node, the setup of cross-connects between add/drop ports and outbound/inbound nodal degrees does not prevent other cross-connects from being set up; if there is a free add/drop port and a free wavelength on an outbound/inbound degree, a cross-connect can always be set up within the node. Contentionless and directionless feature enables efficient use of all the tunable access resources for on-demand and high bandwidth network configuration and simplify the network architecture. A Contentionless ROADM design removes wavelength restrictions from the add/drop portion of the ROADM node so that a transmitter can be assigned to any wavelength if the number of channels with the same wavelength is not more than the number of degrees ( switching direction ) in the node. A degree is another term for a switching direction and is generally associated with a transmission fiber pair. It guarantees that only one add/drop structure is needed in a node. Network planning is simplified since any add/drop port can support all colors and connect to any degree. Photonic switches and WSSs can be used to construct a colorless, directionless, and Contentionless ROADM node. It should be noted that with a colorless, directionless, and Contentionless ROADM node, constraints on wavelength assignment are only removed from the add/drop structure. It is shown in Figure 7, this architecture is like the WSS based Colorless & Directionless ROADM architecture, except the design at the local add/drop site. In this CD&C

ROADM architecture, the WSS and the multi-port splitter combiners at the add/drop location are replaced by the PXC optical switch (shown in Figure 7). All the wavelengths coming along every direction encounter a 1x8 splitter. Three ports of the splitter are connected to the WSS along the other three directions, while the fourth port is connected to one of the input ports of the PXC placed at the local add/drop site. The output ports of PXC are connected to the WSS along the corresponding directions. The Colorless, Directionless and Contentionless ROADM architecture not only offers all the features that are offered by both the PXC and the WSS based ROADM solutions, it also addresses their inherent deficiencies. There are multiple advantages of this CD&C ROADM architecture as the architecture supports multicast of wavelengths coming from any direction and those that are added at the local node A. The PXC which is used for the local add/drop provides the Contentionless add/drop access in addition to Colorless and Directionless add/drop with a provision for the modular growth of the tunable transponders depending on the number of channels to be dropped/added. This results in a better wavelength utilization as the same wavelengths carrying different information can now be sent to different directions. Also, the optical power loss for the add/drop wavelengths is significantly lesser compared to the WSS based ROADM architecture. Because of this, lesser gain of amplification is required at various amplifiers placed at each node in the network. Another advantage is that this CD&C architecture eliminates the need for many WSS modules and splitter combiners at the local add/drop site of every node. This results in a drastic reduction in the service providers' CAPEX.

### 2.2.4 Flex grid ROADM

In flex-grid networks, optical connections for different line rates, spectral widths and modulations can coexist in the same infrastructure. Optical connections are transparently routed by Reconfigurable Add/Drop Multiplexers (ROADMs). Flex-grid ROADMs are enabled by state of-the-art evolution from original Wavelength Selective-Switches (WSS), designed for fixed-grid applications, to WSSs that operate in flexible grids. Broadcast-and-select (B&S) flex-grid ROADMs are subject to the same internal blocking as their fixed grid counterparts, and this internal blocking can be also reduced by augmenting the number of add/drop transponder banks. A lightpath originates at an E/O transmitter in the ingress or add node and terminates at an O/E receiver in the egress or drop node. Lightpaths are allocated over a wavelength in each traversed fiber and are optically switched or bypassed at intermediate nodes.

Flex-grid or elastic optical networks are the foreseen near-future evolution of transparent networks, enabled by the advent of new coherent modulation formats such as Nyquist WDM [4]. In conventional transparent optical networks (fixed grid), a lightpath has a fixed line rate, typically 10, 40 or 100 Gbps, and is allocated in a 50 GHz or 100 GHz channel within the DWDM ITU grid. In contrast, in flex grid networks, lightpaths are allocated over a contiguous spectrum composed of 12.5 GHz slots (according to ITU-T Recommendation G.694.1). The line rate of the lightpath depends on the modulation employed and the spectral width assigned. A modern design trade-off appears in the selection of the transmission modulation of a lightpath: more robust modulations like BPSK have a longer reach (km), at a cost of a lower spectral efficiency (bps/Hz) respect to more sophisticated modulations like 16-QAM.
ROADMs are feasible today in the flex-grid context, thanks to the state-of-the-art evolution from original WSS devices, designed for fixed-grid applications, to e.g. Liquid Crystal on Silicon (LCoS)- based WSSs that perform the selection feature in flexible grids.
A ROADM provides flexibility to switch optical channels that traditionally have center frequencies as defined by the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T)grid. According to ITU-T G.694.1, the frequency of an optical channel is defined with respect to a reference frequency of 193.10 THz, or 1552.52 nm in wavelength. The frequency difference between adjacent optical channels, referred to as channel spacing, can range from 12.5 to 100 GHz and wider. 100 and 50 GHz are common channel spacings used in optical networks today. Most tunable lasers used in transmitters are designed to have frequency locking mechanisms that align the frequency of the channel with the grid. As the data rate of an optical channel continues to increase, advanced modulation has successfully squeezed 40 Gb/s channels and 100 Gb/s channels into a 50 GHz channel spacing, that was originally designed for 10 Gb/s channels. To fit channels with high data rates into small channel bandwidths, especially for the 100 Gb/s signals, the modulation format has moved away from classical on-off keying. Multilevel amplitude and phase modulation have been introduced to reduce the overall optical bandwidth of a channel. The most prominent example is the PMQPSK format generally used for 100 Gb/s channels. Since with PM-QPSK the symbol rate of the 100 Gb/s signal is only one fourth the data rate [5], the modulated signal fits into a 50 GHz channel. By using 50 GHz channel spacing for 100 Gb/s channels, the optical spectral efficiency has increased 10 times to 2 b/s/Hz when compared to 10 Gb/s signals. Foreseeing higher channel data rates and greater spectral efficiency requirements soon, innovation in ROADM designs will be required as shown by the concepts of tunable channel bandwidth and "elastic optical

path”. Since an increase in spectral efficiency of the modulation format requires an remarkable increase in SNR it is not likely that channels with data rates beyond 100 Gb/s will be designed with a 50 GHz channel spacing for long-haul network transmission distances. Flexibility to increase the symbol rate as well as spectral efficiency will allow optimizing the reach of long-haul optical channels with a data rate higher than 100 Gb/s such as 400 Gb/s and 1 Tb/s. To further increase spectral efficiency, the required bandwidth of these channels with ultrahigh data rates should be minimized. For example, the bandwidth of a 400 Gb/s channel (using PM 16-QAM with 56–64 GBaud) is likely to require only a 75 GHz channel spacing, while a 1 Tb/s channel (using PM 32-QAM with 112–128 GBaud) would require only a 150 GHz channel.

## *2.3 Coherent Transmission System*

A coherent optical transmission system is characterized by its capability to do “coherent detection,” which means that an optical receiver can track the phase of an optical transmitter (and hence “phase coherence”) to extract any phase and amplitude information carried by a transmitted signal. Coherent detection is well known in wireless communication systems. In those wireless systems, a radio frequency (RF) local oscillator (LO) is tuned to “heterodyne” (“heterodyne” is a signal processing technique which combine a high-frequency signal operating at f1 with another operating at f2 to produce a lower frequency signal at (f1 – f2), with a received signal through an RF mixer, as shown in Figure 8 (a), so that both the amplitude and phase information contained in an RF carrier can be recovered in the following digital signal processor (DSP).

For an optical coherent system, a narrow-linewidth tunable laser, serving as a LO, tunes its frequency to “intradyne” with a received signal frequency through an optical coherent mixer, as shown in Figure 8 (b), and thereby recovers both the amplitude and phase information contained in an optical carrier. Here, “intradyne” means that the frequency difference between a LO and a received optical carrier is small and within the bandwidth of the receiver but does not have to be zero. This implies that the frequency and phase of a LO do not have to be actively controlled to an extreme accuracy, therefore avoiding the use of a complicated optical phase locked loop.

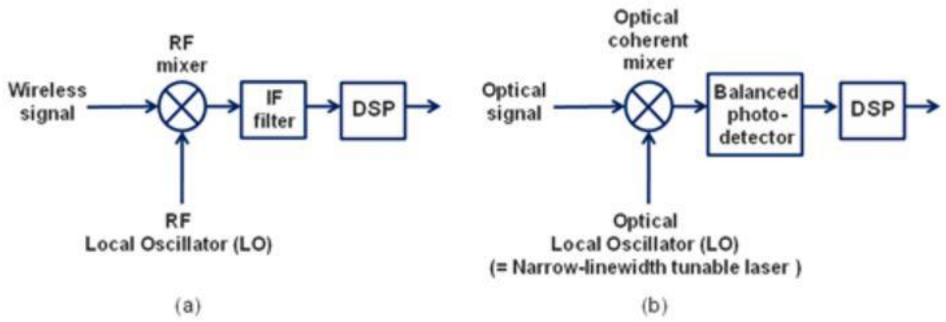



Figure 8 : Simple coherent detection schemes for (a) wireless (b) optical coherent system. [9].

Later, in the following section coherent transmitter and coherent receiver are described. And, capacity and flexibility of coherent transmission system.

### 2.3.1 Architecture of coherent transponder

This Coherent detection implies that sources must be single frequency, otherwise frequency and phase cannot be defined. The light generated by single frequency laser and propagating through a single mode fiber (SMF) can be fully defined by its amplitude, frequency, phase and state of polarization (SOP). When light from two coherent (single frequency) sources is coupled into one fiber, the propagation axis and the pointing vector will overlap. Inference can now take place onto a photo diode, giving coherent optical detection.

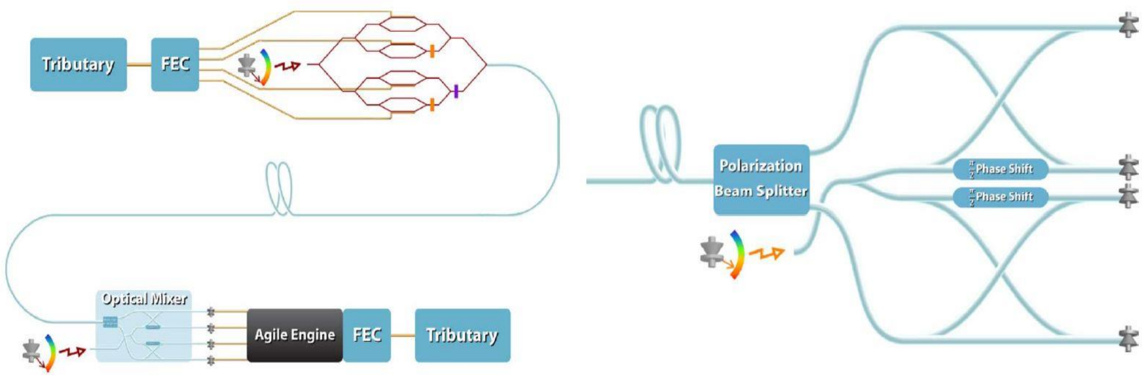



Figure 9**:** Typical Coherent modem and front end of coherent receiver. [9]

Considering a high-level block diagram for one channel of a coherent modem, tributary signal (such as 10, 40, or 100 Gb/s standard formats), are multiplexed and pre- coded with FEC (Forward error correction). These bits are then multiplexed to a baud value of 32 GBaud or 64

GBaud. Four data streams modulate the light from a tunable laser, encoding in phase and quadrature signals on X and Y polarization. If we look through the coherent receiver we can know how the four data streams are combined and imposed on a single optical signal. The signal is first split along orthogonal polarization directions by means of a polarization beam splitter which serves as a local polarization reference. Each signal polarization is further split and combined with each of two mutually orthogonal phases of co-polarized light from the local oscillator. It is accomplished using splitters, phase shifters and combiners to deliver four orthogonal optical signals to the four photo-diodes. The local oscillator must be tuned so that its frequency is within a few hundred MHz of the transmitter laser frequency for acquisition in the digital signal processing (DSP) engine. The four electrical signal dimensions (two phases and two polarization dimensions) are then a complete set representing the optical signal which can be demodulated.

### 2.3.2 Coherent Transmitter

Basically, Coherent transmitter is consisting of Amplitude/Phase Modulation and Polarization Multiplexing. High-order Amplitude/Phase Modulation, Many of the optical hero experiments of the early 2000s were aimed at increasing the data rate per WDM channel beyond what was possible using 10G Intense Modulation-Direct Detection(IM-DD). The 10G barrier was due to the sensitivity of IM-DD to fiber impairments as the data rate was increased, and so alternative modulation techniques were investigated. Phase shift keying modulation, such as DPSK and differential quadrature phase-shift keying (DQPSK), were favored because, in the case of DPSK, there is a significant advantage in the required optical signal-to-noise ratio (OSNR) as compared to IM-DD. In addition, by encoding more amplitude/phase changes in the carrier, it is possible to increase the number of bits carried in each symbol, and the sensitivity to fiber impairments relates to the symbol rate (not directly to the bit rate). Figure 10 shows the basic principle of amplitude/phase modulation in which there is a simple transmitter circuit that uses a Mach-Zehnder modulator (MZM) to encode one data stream onto the optical carrier.

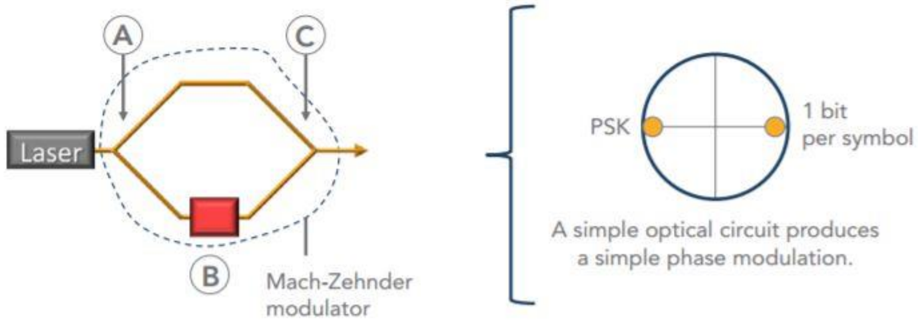



Figure 10: A Single Mach-Zehnder Modulator and the Resulting Phase Constellation. [8]

This is known, depending on the exact details of the implementation, as phase-shift keying (PSK), binary phase-shift keying (BPSK), or if the data is differentially encoded so that the bits are represented by phase changes, and not the absolute phase states, DPSK. Light from the laser enters the MZM at Point A and is divided in two so that it passes over the upper and lower arms of the waveguide. At Point B, a signal can be applied to the waveguide that changes the refractive index, and thus the effective velocity of the light at that point. Therefore, when the two parts of the light are recombined at Point C, there is a series of phase changes encoded onto the light that is directly related to the input signal. The right-hand side of Figure shows a simple phase constellation of PSK. In each clock cycle, if a phase symbol exists on the left of the constellation, then the receiver would interpret this is a 1. If the phase symbol exists on the right of the constellation then the receiver interprets this bit as a 0. In contrast, a differential system would look for phase changes. A more complex optical transmitter is shown in Figure 11.

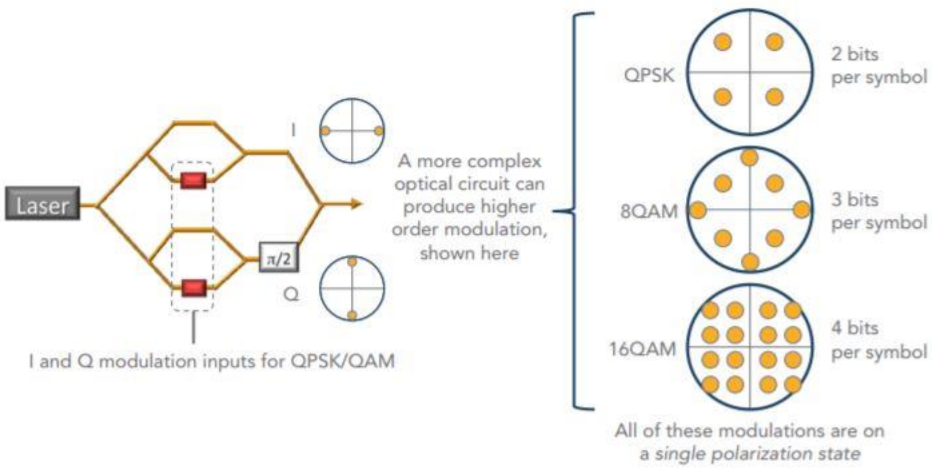



Figure 11: High-order Modulation Using a Nested Mach-Zehnder Structure. [8]

Here we see a series of nested MZM components, known as a Nested Mach-Zehnder, and each red block represents a data input point for a portion of the overall modulation signal [8]. The upper MZM forms is in-phase (I) signal and the lower MZM (passing through a π/2, or 90-degree phase shift) forms the quadrature (Q) signal for QPSK and quadrature amplitude modulation (QAM). By using more complex drive signals, this same Nested Mach-Zehnder structure can be used to generate all the amplitude/phase modulation techniques shown on the right of Figure 11. This move toward higher-order modulation allows more bits to be carried by each symbol. QPSK carries two bits in each symbol. However, by doubling the number of ampitude states we do not double the number of bits per symbol. While this might not seem self-evident at first, consider a binary representation, as shown in the table below.

Polarization Multiplexing The modulation constellations and spectral efficiencies shown in Figure 10 and Figure 11 are for a single polarization signal. Fiber can be regarded as a circular waveguide and as such it supports two orthogonal polarizations. By selectively transmitting modulated signals using polarization multiplexed (PM) carriers, we can effectively double the spectral efficiency of a given modulation technique while using the same PM receiver. So, compared to the single polarization signals in Figure 10 and Figure 11, PM-BPSK, PM-QPSK, PM-8QAM and PM-16QAM modulation techniques offer two, four, six and eight bits per "symbol" respectively. In this case, a symbol is the combination of amplitude/phase states and polarization states, which can be referred to as a "dual-pol symbol."

Figure 12 shows a schematic of a transmitter that would be required to generate, for example, a 100G single carrier PM-QPSK modulation constellation. Notice that the light from a single laser signal is split and sent into four separate Mach-Zehnder modulators. The upper and lower portions of this super Mach Zehnder structure each generate a QPSK signal. The signals are then sent into a polarization beam combiner so that the signal from the upper half of the circuit becomes X-polarized, while the signal from the lower half of the circuit becomes Y-polarized. Note that the overall bit rate of the PM-QPSK transmitter is four times the symbol rate of each MZM. This division of processing is especially useful in allowing a high-data-rate digital signal to be divided into multiple parts, so that lower-speed electro-optics can be used. The signal input points are shown by the red and green boxes in Figure 12. The resulting 100G PM-QPSK signal is shown on the right-hand side of Figure 12. Note that the red and green colors of the peaks are merely to illustrate the two different polarization states. The signals are, in fact, on the same wavelength.

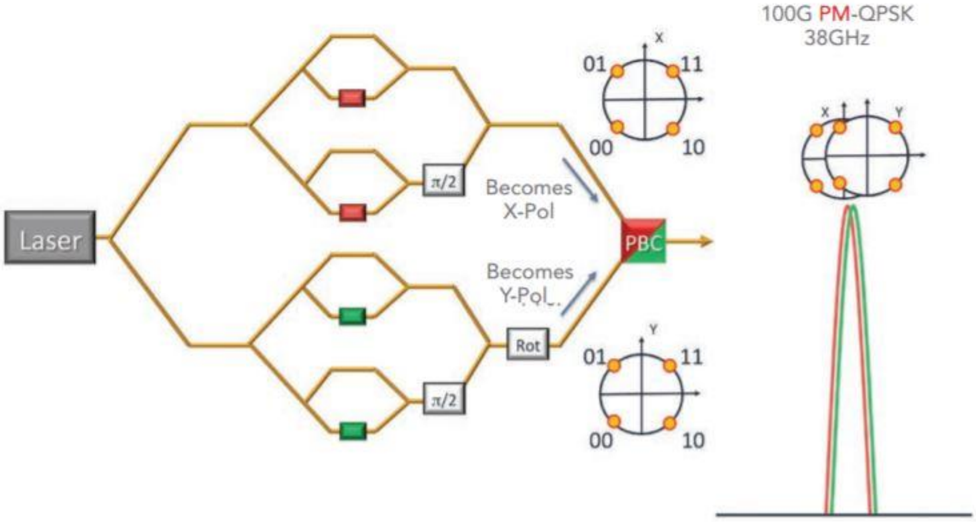



Figure 12: Schematic of 100G, Single-carrier, PM-QPSK Transmitter, and the Resulting Phase Constellations on Each Polarization State. [8]

50 GHz grid defined in ITU G. 694.1. An alternative implementation of 100G transmission, which was used by some commercial implementation. This is a dual-carrier implementation, in which two, 50G single carrier data streams are transmitted in the equivalent of a 50GHz WDM channel. This has effectively the same spectral efficiency as the single-carrier implementation shown in Figure 12, and it has at least as good optical reach. But the primary advantage of a dual carrier implementation is that the opto-electronics only need to operate at 12.5 gigabaud (GBaud), plus overhead, compared to the 25 GBaud plus overhead needed in a single carrier implementation. Note that 25 GBaud opto-electronics is currently considered state of the art very much, and as a result has a much higher cost, higher power consumption, and lower long-term reliability than a less “over-clocked” component. If a manufacturer is limited to using discrete optical components, then a single carrier implementation is advantageous—despite the drawbacks of the opto-electronics. The use of photonic integration removes the pressure caused by high optical component counts and allows a WDM manufacturer to make the most appropriate implementation decision.

### 2.3.3 Coherent receiver/Coherent detection

Coherent detection is a linear process, and linear equalization can be employed to effectively compensate for CD and PMD. Figure 13 shows a functional block diagram of a modern optical coherent receiver.

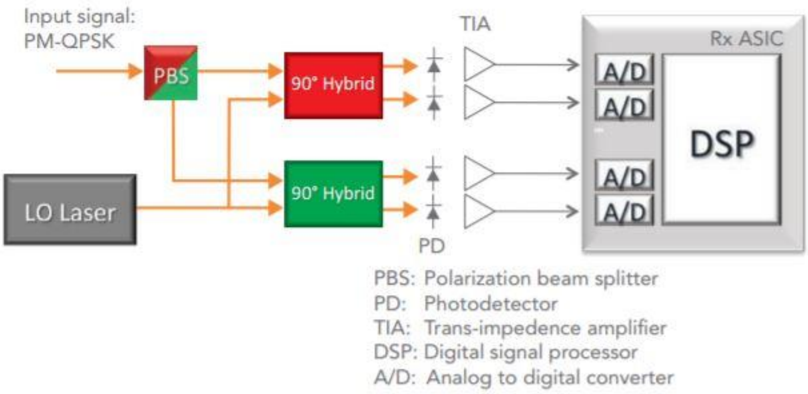



Figure 13: Schematic of a Single-carrier Coherent Detector Including Polarization Demux. [8]

The incoming optical signal passes through a polarization beam splitter (PBS), which divides the signal into two orthogonal polarization signals. One of these signals now consists of the X-polarized component, and the other consists of the Y-polarized component. Each component is now passed into a 90-degree optical hybrid circuit. Each optical hybrid consists of a two-by-two optical coupler with a 90-degree phase delay function implemented on one arm of the coupler. This circuit allows the I and Q components of the signal to be extracted because of the interference generated by the local oscillator. It is this extraction process facilitated by the local oscillator laser that is the essence of coherent detection. The phase signals are now converted from the optical domain into the electronic domain using a series of balanced photodetectors. Each of these signal passes through three elements: 1) Intensity noise, 2) A digital converter representing the power of the local oscillator and 3) The coherent signal. If a single photodetector was used, it would be necessary to employ a local oscillator laser with 20 to 25 decibels (dB) more power than the incoming signal for the resulting coherent signal term to dominate. By using a balanced photodetector, it is possible to employ a much less powerful local oscillator. Note that the phase and frequency of the LO does not have to be actively controlled, which would be necessary in a conventional phase lock loop implementation. In fact, the LO frequency only needs to be within approximately 1 GHz of the incoming signal, and the speed of frequency adjustment can be relatively slow. To recover the transmitted bits, carrier phase synchronization is performed in the digital signal processor (DSP), and this mode of coherent detection without active optical phase lock loop is known as intradyne coherent detection. In addition to a huge increase in detector sensitivity, a coherent detector can be tuned to receive only a specific wavelength, allowing for an elevated level of signal rejection from neighboring WDM channels. In ITU grid-based systems this advantage may not be of primary concern; but it becomes extremely useful as we move towards grid less channels. The baseband electrical signals are digitized by four high-speed ADCs, and the resulting digital signal samples are passed into a powerful DSP.

The ability to process the received optical signal in the digital domain represents one of the biggest differentiators for commercial coherent WDM implementations. In implementations such as the one shown in Figure 14, the receive function of a Flex Coherent DSP performs three critical functions.

1) Chromatic dispersion compensation. The DSP can compensate for practically any amount of chromatic dispersion that would be found in real fibers. This opens the possibility of removing dispersion compensating fiber (DCF) from routes that use coherent detection. In fact, coherent systems work better for the links without DCFs. This is because higher chromatic dispersion will help to offset non-linear effects such as self-phase modulation (SPM) and cross phase modulation (XPM), and thereby increase the effective reach of the signal. Chromatic dispersion is static, and the dispersion compensation dynamic control can be done at low speed within the DSP. Note also that chromatic dispersion compensation is the same for the X-polarized and Y-polarized parts of the signal, and there is no cross-coupling between the two polarizations.

2) Polarization mode dispersion compensation. After chromatic dispersion compensation, the DSP compensates for dynamic Jones rotation (where the polarization state of the signal has changed on its journey along the fiber) and PMD. Once again, it has been shown that a high-quality DSP algorithm is able to compensate for even the highest levels of practical PMD observed in fibers today. In practice, PMD transients are faster than chromatic dispersion variations, and as such, PMD compensation is dynamically updated at medium speed, of the order of a few kilohertz (kHz).

3) Intradyne carrier recovery. As explained above, in modern optical coherent detection the preferred form of signal mixing is known as intradyne detection, in which a free-running local oscillator is used. Carrier recovery between the receive signal and the local oscillator is performed digitally in the DSP. In an intradyne implementation, the DSP can track local

oscillator phase noise for both the transmitter and the local oscillator laser by performing carrier recovery. The offset frequency and the phase noise will be tracked by the digital carrier recovery in the DSP. This carrier recovery process has the highest speed of all the demodulation functions in the DSP.

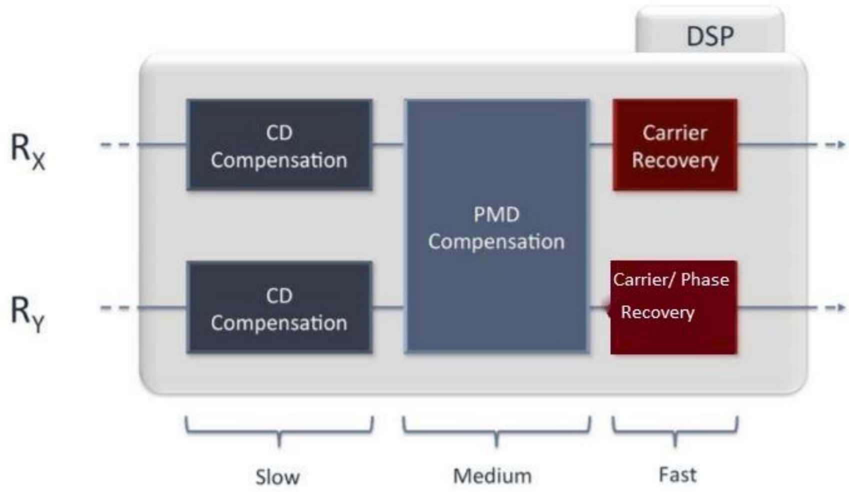



Figure 14: Flex Coherent Processor Received Functional Blocks. [8]

These three functions, along with their performance requirements, are shown in Figure 14. In this Figure $R_X$ represents the received X-polarization signal, and $R_Y$ represents the received Y-polarization signal.

### 2.3.4 Capacity and Flexibility of coherent system

Several methods are available to increase the overall capacity of a system. The most obvious one is to widen the amplified spectrum. For example, adding an L-band over a C-band system, more than doubles the overall capacity at a constant spectral efficiency (the C-band is 35 nm wide, and the L-band is 60 nm wide). Most currently deployed commercial systems deliver a spectral efficiency of about 1 to 5 bits⁄s⁄Hz, depending upon the modulation format . The paths to improve the spectral efficiency are threefold: first, the transceiver internal noise, caused by quantization noise, RF driver nonlinearity, bandwidth limitation, Tx and Rx I/Q errors, clock jitter, and DSP impairments, needs to be reduced. This is especially important in short-distance transmissions, where the link accumulated noise and distortion are relatively small with respect to the internal noises. Second, advanced modulation formats with higher noise tolerance and stronger FEC, with a higher coding gain, need to be developed. Third, fiber nonlinearity mitigation and compensation techniques can be used to reduce the fiber nonlinear noise. In addition to higher capacity per wavelength and longer optical reaches, finer granularity in data rates also lowers the cost per bit. This cost-effectiveness improvement occurs by enabling a more complete exploitation of the signal-to-noise ratios (SNRs) available in diverse and dynamic optical networks.

Considering Advance modulation format Two-dimensional modulation formats have been used in the early generations of coherent systems for their implementation simplicity. Since then, the application space of coherent systems widened and higher tolerance to noise was required. To this effect, multi-dimensional modulation formats have been proposed, since they have the potential of achieving the needed higher noise tolerance, smaller data rate granularity, and mitigation of fiber nonlinearities.

# 3 Optical Networking

An optical network connects computers (or any other device which can generate or store data in electronic form) using optical fibers. Optical fibers are essentially very thin glass cylinders or filaments which carry signals in the form of light (optical signals). To facilitate data communication, an optical network also includes other optical devices to generate optical (electrical) signals from electrical (respectively optical) data, to restore optical signals after it propagates through fibers, and to route optical signals through the network. Optical fibers are connected between transmitter and receiver. Figure 15 In the transmitter section signal is converted from electrical to optical and in the receiver section the signal is converted from optical to electrical.

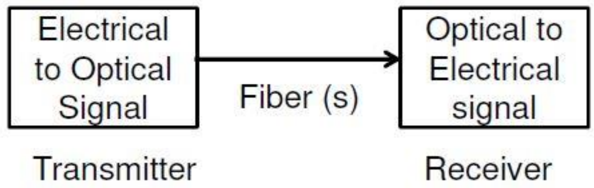



Figure 15: Transmitter connected to receiver in an optical network.

## 3.1 Network topology

In an optical network, all possible sources or destinations of data are called end nodes. Another vital component of an optical network is the optical router. Every router node has several input (output) fibers, each carrying one or more incoming (outgoing) optical signals. The purpose of a router is to direct each incoming optical signal to an appropriate outgoing fiber. An example of a simplified model of a second-generation optical network is shown in Figure 16 , where a circle represents an end node, a rectangle represents a router node and a directed line represents a fiber. These fibers are unidirectional and the arrow on the line gives the direction in which optical signals can flow. Such a diagram is called a physical topology since it shows the major physical components of the network.

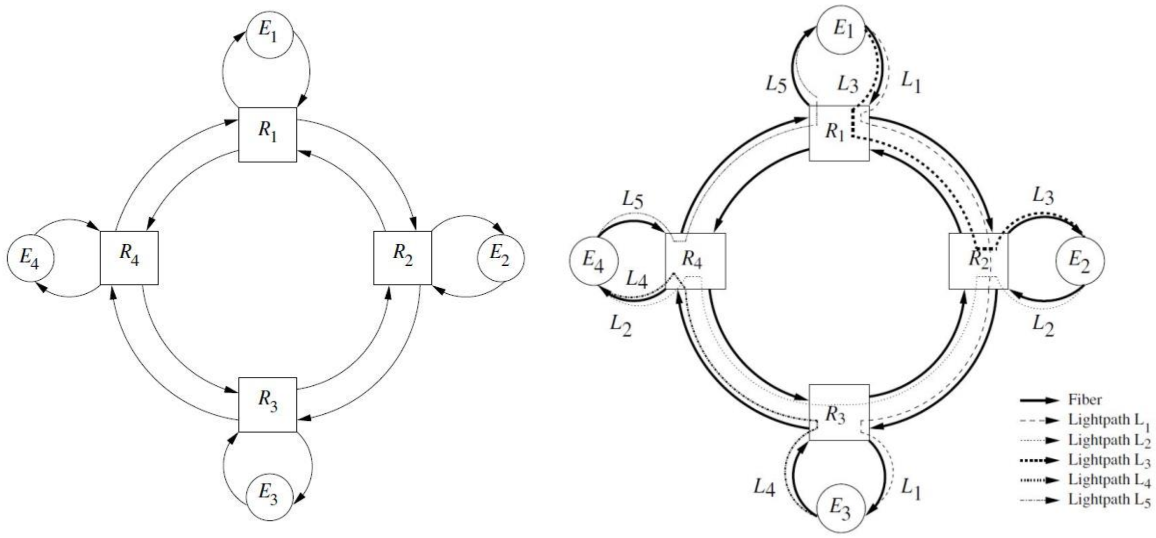



Figure 16: Physical topology and lightpath on physical topology.

In a wavelength routed WDM network, end users communicate with one another via all optical WDM channels which are referred to as lightpaths. A lightpath is used to support a connection in a wavelength routed WDM network, and it may span multiple fiber links. In the absence of wavelength converters, a lightpath must occupy the same wavelength on all the fiber links through which it traverses; this property is known as wavelength continuity constraint. Illustrates a wavelength routed network in which lightpaths have been set up between pairs of access node on different wavelength.

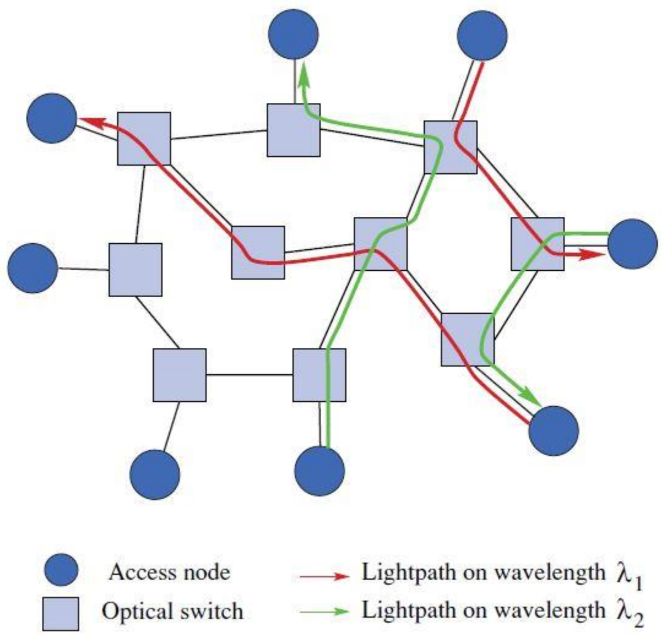



Figure 17: WDM network with lightpath connection.

A lightpath is an optical connection from one end node to another, used to carry data in the form of encoded optical signals. Such a lightpath always starts from an end node, traverses many fibers and router nodes, and ends in another end node.

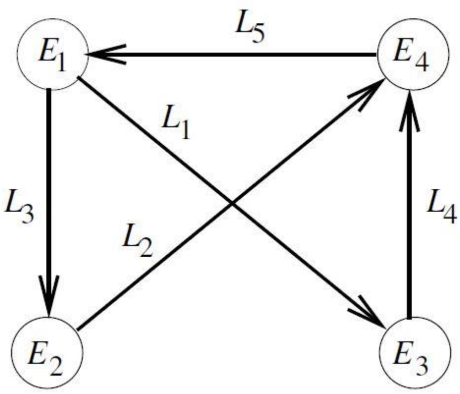



Figure 18: Logical topology.

Graph representation, a graph is a set of edges. For example, {(n1; n2); (n2; n3); (n4; n4)} is a representation which stands for a 4-node graph with 3 edges, one of which is a self-loop. It is also easy to see that this graph is directed and disconnected, and it has a three-node weakly connected component, namely {n1, n2, n3}. Assume that n is the number of nodes in each graph, and m is the number of edges.

An adjacency matrix is a n * n matrix A, such that A (i; j) = 1 if i is connected to j and A (i; j) =0, otherwise. The 1s in the matrix stand for the edges. If the graph is undirected, then the matrix is symmetric, because A (i; j) = A (j; i) for any i and any j. While usually this is a 0-1 matrix, sometimes edge weights can be indicated by using other numbers. Most generally the adjacency matrix has zeros and positive entries. An edge list is a matrix representation of the set of edges. For the toy example {(n1; n2); (n2; n3); (n4; n4)} the edge list representation is [n1 n2; n2 n3; n4 n4]. Edge lists can have weights too.

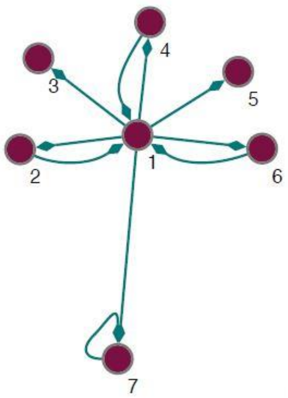
$$edgelist = \begin{matrix} n1 & n2 & 0.5 \\ n2 & n3 & 1 \\ n3 & n4 & 2 \end{matrix}$$

Note that the edge list is also known as sparse column format, in which only non-zero entries of the adjacency matrix are stored, as well as the coordinates where they occur. The adjacency list is the sparsest graph representation. For every node, only its list of neighbors is recorded. The adjacency list representation of the four-node example above is:

adjList{n1} = [n2]; adjList{n2} = [n3]; adjList{n4} = [n4].

The incidence matrix I is a table of nodes (n) versus edges (m). In other words, the rows are node indices and columns correspond to edges. So, if the edge e connects nodes i and j, then I (i; e) = 1 and I (j; e) = 1. For directed graphs I (i; e) = -1 and I (j; e) = 1, if i is the source node and j the target. For above example,

$$I = \begin{array}{c|ccc} & e_1 & e_2 & e_3 \\ \hline n_1 & -1 & 0 & 0 \\ n_2 & 1 & -1 & 0 \\ n_3 & 0 & 1 & 0 \\ n_4 & 0 & 0 & 1 \end{array} .$$




$$\text{edge list} = \begin{array}{c} 1 \to 2 \\ 2 \to 1 \\ 1 \to 3 \\ 1 \to 4 \\ 4 \to 1 \\ 1 \to 5 \\ 1 \to 6 \\ 6 \to 1 \\ 1 \to 7 \\ 7 \to 7 \end{array} \quad \text{adjacency} = \begin{array}{ccccccc} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}$$

$$\text{adj list} = \begin{array}{cc} \{1\} \to & 2, 3, 4, 5, 6, 7 \\ \{2\} \to & 1 \\ \{3\} \to & \emptyset \\ \{4\} \to & 1 \\ \{5\} \to & \emptyset \\ \{6\} \to & 1 \\ \{7\} \to & 7 \end{array} \quad \text{incidence} = \begin{array}{c|cccccccccc} & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & e_7 & e_8 & e_9 & e_{10} \\ \hline n_1 & -1 & 1 & -1 & -1 & 1 & -1 & -1 & 1 & -1 & 0 \\ n_2 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ n_3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ n_4 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ n_5 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ n_6 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ n_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{array}$$

Figure 19: Most common graph representations: edge list, adjacency matrix, adjacency list and incidence matrix, Example of 7-node directed graph, with one self-loop. [29]

An optical transmission section consists of optical fiber and optical amplifier. In Figure 20, There are one or more optical transmission section in one optical multiplex section. A single optical transmission section is called optical link. In the both end of optical multiplex section there are WDM multiplexer. Couple of optical multiplex section are inter connected with optical cross connect. Basically, an optical channel is the combination of this all section where two end

WDM multiplexer is present. At the input section of WDM multiplexer section, the signal is normally tributary signals.

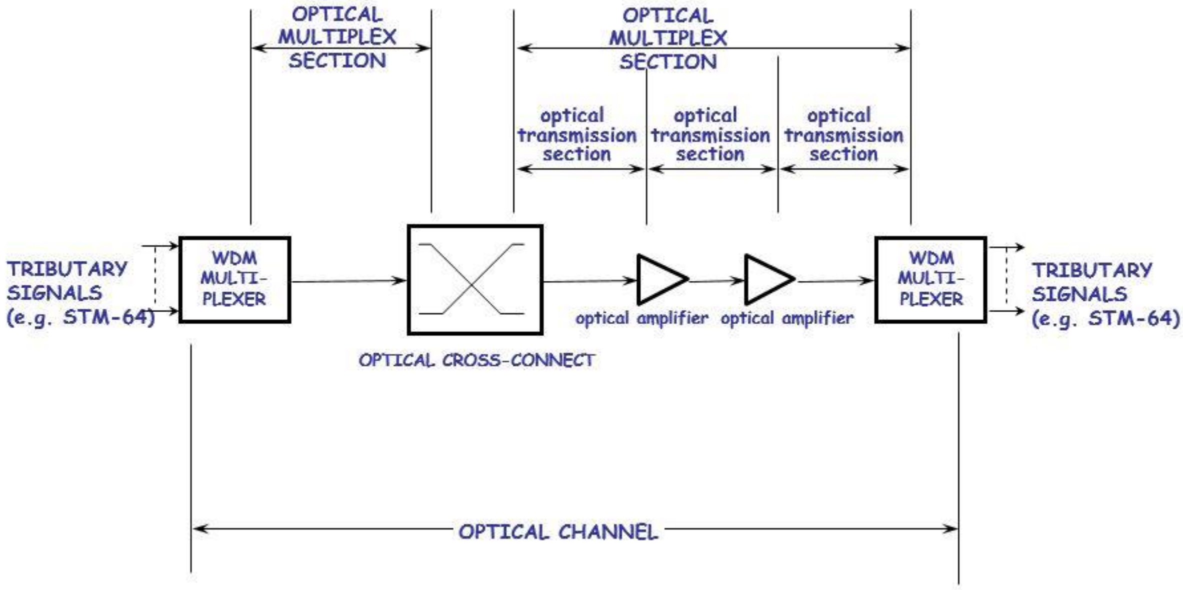



Figure 20: Optical transport network layer architecture.

### 3.1.1 Optical fiber links

The optical link design is combining the various optical components, so that information can be transmitted usefully. The usefulness of the transmission can be defined in terms of some characteristic parameters. The user generally specifies the distance over which the information is to be sent and the data rate to be transmitted. The designer then should find the specification of the system components. The designer generally should define some additional criteria either as per the standards or as per the user specifications.

The design criteria are given following: (1) Primary design criteria, which defines the Data rate and link lengths. (2) Additional design length. Modulation format (analog or digital). System fidelity defines the correctness of the data received at the receiver. For digital transmission, it is measured it is measured by the Bit error ratio (BER). The BER is the ratio of number of bits in error and total number of bits transmitted. For analog system, the quality parameter is the signal to noise ratio (SNR). Cost is one of the principal issue of the link design. There are 3 components for cost issue, a) components b) installation c) maintenance.

The conventional fiber exhibits a secondary minimum around 1310 nm and an absolute minimum near 1 550 nm. In older fiber (e.g. ITU-T G.652.B) a strong peak of attenuation was present around 1383 nm due to the presence of the residual water vapor in silica (OH ion). In modern low water peak fiber (e.g. ITU-T G.652.D) the concentration of the OH ion is drastically reduced and the attenuation peak around 1383 nm has practically disappeared. The low water peak fiber allows the possibility of using a larger wavelength range in respect of older fibers, for WDM system applications. The attenuation coefficient is specified with a maximum value at one or more wavelengths in both the 1310 nm and 1550 nm regions. The attenuation coefficient may be calculated across a spectrum of wavelengths, based on measurements at a few (3 to 4) predictor wavelengths. This procedure is described in Recommendation ITU-T G.650.1 and an example is given in Recommendation ITU-T G.650.1.

Polarization mode dispersion (PMD) is related to the differential group delay (DGD), the time difference in the group delays between two orthogonal polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems. In ideal circular symmetric fibers Figure 21, the two polarization modes propagate with the same velocity. However, real fibers cannot be perfectly circular and can undergo local stresses; consequently, the propagating light is split into two polarization modes.

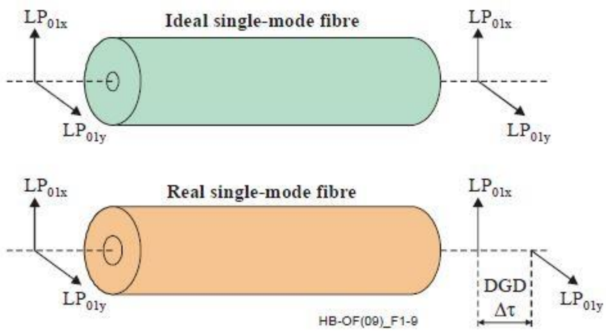



Figure 21: DGD due to the two polarization modes propagating at different velocities.

### 3.1.2 Optical cross connects and passive nodes

Optical channel cross-connecting is a key function in most communications systems. In electronic systems, the electronic cross-connecting fabric is constructed with massively integrated circuitry and is capable of interconnecting thousands of inputs with thousands of outputs. The same interconnection function is also required in many optical communications systems. Optical (channel) cross-connection may be accomplished in two ways:

1. Convert optical data streams into electronic data, use electronic cross-connection technology, and then convert electronic data streams into optical. This is known as the elctronic switching.
2. Cross-connect optical channels directly in the photonic domain. This is known as all-optical switching.

Optical cross-connect devices are modeled after the many-port model: that is, N input ports and N output ports, with a table that defines the connectivity between input and one or more outputs. Mathematically, this model may be represented by a matrix relationship. Figure 22: Modelling of an optical cross connect, Mathematically and symbolically. illustrates the model and the matrix of a cross connecting device, where $I_K$ is the amplitude of light at input port K, $0_L$ is the amplitude of light at output port L, and $[T_{IJ}]$ is the transmittance matrix. In general, the transmittance terms $T_{IJ}$ are functions of the absorption and dispersion characteristics of the connectivity path. Ideally, the $T_{IJ}$ terms are 1 or 0, signifying connects or no connect, respectively, with zero connectivity loss and zero dispersion.

$$\begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_N \end{bmatrix} = \begin{bmatrix} T_{11} \cdots T_{1N} \\ T_{21} \cdots T_{2N} \\ \vdots \quad \vdots \\ T_{N1} \cdots T_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}$$

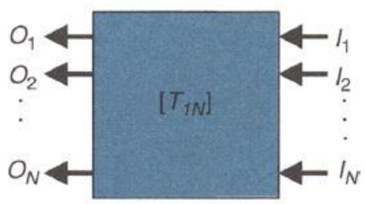



Figure 22: Modelling of an optical cross connect, Mathematically and symbolically.

The quality of an optical network is determined by the performance of each of its individual components. Nodes in this network are one of the key components of the physical network. A “node” is defined as a point of intervention in the network, e.g. it occurs at each opening or end of a cable jacket. “Passive” applies to nodes that do not contain active electronics or other devices that are exothermic. Examples of passive nodes are optical distribution frames, joint closures for underground and aerial applications, street cabinets etc. Each node shall can perform its expected function in the network, while exposed to the environment in which it is intended to reside.

To achieve and maintain a suitable network performance level the passive optical nodes should be able to properly store and protect all compatible passive devices without altering their performance characteristics. Examples of passive devices are:

i) splices and splice protectors
ii) optical connectors.
iii) other optical components.

To obtain an end-to-end reliable network, all different network nodes shall be evaluated using the same methods and metrics. A network node should be able to fulfil its optical functionalities, including the ability to be reconfigured, in all conditions of the environment, in which the node will reside.

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### 3.1.3 Transparent vs translucent network

Transparency, in the strict sense, implies that the physical medium (an optical fiber) should support end-to-end communication of data, independent of bit rates and signal formats. Transparent WDM networks readily allow express signals to bypass extensive electronic signal processing at intermediate nodes. However, the quality of an optical signal degrades as it travels though several optical components along its lightpath from its source to destination. The causes of these degradations include optical-fiber nonlinearities; chromatic and polarization-mode dispersion; noise accumulated due to amplified stimulated emission (ASE) from optical fiber amplifiers (e.g. erbium-doped fiber amplifiers (EDFA)); effects of non-flat gain profile and gain saturation in fiber amplifiers; cross-talk introduced at cross connects; etc. To overcome these impairments, "long-distance" lightpaths may require signal regeneration, at one or more intermediate locations in the network, to "clean up" the signals. Signals are regenerated either through an opto-electronic conversion followed by an electro-optic conversion function (OECF) or entirely in the optical domain.

In a translucent network, a signal from the source travels through the network "as far as possible" before its quality (say, bit-error rate (BER)) degrades, thereby requiring it to be regenerated at an intermediate node. The same signal could be regenerated several times in the network before it reaches the destination. Note that a single optical hop in a translucent network could span one or more fiber links and may even span the entire source-destination route, under the right conditions. We assume that the network resources available are identical in all three cases. Signal regeneration is achieved in the network by employing a receiver and a transmitter at an intermediate node, without any special hardware.

## 3.2 Routing

Routing refers to establishing the routes that data packets take on their way to a destination. This term can be applied to data traveling on the Internet, over 3G or 4G networks, or over similar networks used for telecom and other digital communications setups. Routing can also take place within proprietary networks. In general, routing involves the network topology, or the setup of hardware, that can effectively relay data. Standard protocols help to identify the best routes for data and to ensure quality transmission. Individual pieces of hardware such as routers are referred to as "nodes" in the network. Different algorithms and protocols can be used to figure out how to best route data packets, and which nodes should be used. For example, some data packets travel according to a distance vector model that primarily uses distance as a factor, whereas others use Link-State Protocol, which involves other aspects of a "best path" for data. In this following section, different kind of routing algorithms will be discussed briefly.

### 3.2.1 Shortest path (Dijkstra algorithm)

Dijkstra algorithm of shortest path was invented by Edsger Wybe Dijkstra. This algorithm is basically the solution of single source shortest path problem. It is an algorithm for finding the shortest paths between two nodes in a graph, which may represent, for road networks. The algorithm exists in many variants; Dijkstra's original variant found the shortest path between two nodes, but more common variant fixes a single node as the "source" node and find shortest paths from the source to all other nodes in the graph, producing a shortest path tree.

Single source shortest path problem: The problem of finding shortest paths from a source vertex (plural vertices or nodes) v to all other vertices in the graph. Weighted graph G= (E, V). source vertex s ϵ V to all vertices v ϵ V. Solution to the single-source shortest path problem in graph theory: Both directed and undirected graphs. All edges must have non-negative weights. Graph must be connected. Shown in Figure 23.

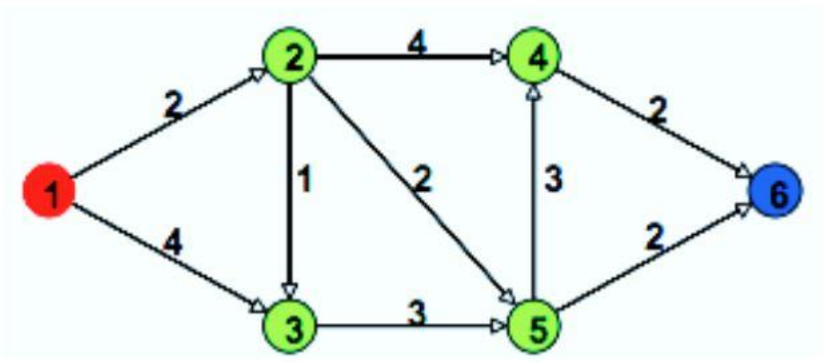



Figure 23. shortest path [17]

**Pseudocode:**

In the following algorithm, the code u ← vertex in Q with min dist[u], searches for the vertex u in the vertex set Q that has the least dist[u] value. length (u, v) returns the length of the edge joining (i.e. the distance between) the two neighbor-nodes u and v.

| | |
|---|---|
| **function** Dijkstra (Graph, source): | |
| create vertex set Q | |
| **for each** vertex v in Graph: | // Initialization |
| dist[v] ← INFINITY | // Unknown distance from source to v |
| prev[v] ← UNDEFINED | // Previous node in optimal path from source |
| add v to Q | // All nodes initially in Q (unvisited nodes) |
| dist[source] ← 0 | // Distance from source to source |
| **while** Q is not empty: | |
| u ← vertex in Q with min dist[u] | // Node with the least distance // will be selected first |
| remove u from Q | |
| **for each** neighbor v of u: | // where v is still in Q. |
| alt ← dist[u] + length (u, v) | |
| **if** alt < dist[v]: | // A shorter path to v has been found |
| dist[v] ← alt | |
| prev[v] ← u | |

| | |
|---|---|
| **return** dist [], prev [] | |

Table 1: pseudo code of Dijkstra's algorithm. [18]

**Output of Dijkstra's Algorithm:**

Original algorithm outputs value of shortest path not the path itself. With slight modification, we can obtain the path (highlighted in blue path) in Figure 24. Value: $\delta$ (1,6) = 6 and Path: {1,2,5,6}

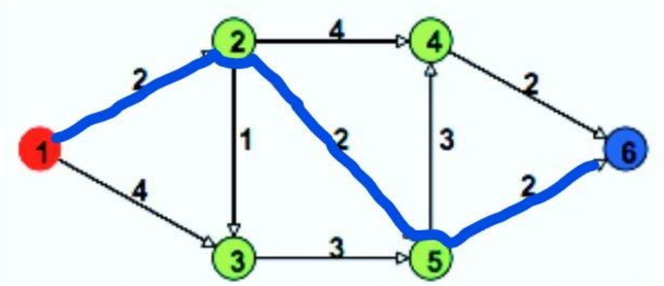



Figure 24: output of the Dijkstra Algorithm.

### 3.2.2 k-shortest paths (Yen's algorithm)

Yen's algorithm computes single source k-shortest loop less paths for a graph with non-negative edge cost. The algorithm employs any shortest path algorithm to find the best path, then proceed to find **k-1** deviations of the path. The algorithm can be broken down into two parts, determining the first k-shortest path, $\mathbf{A^k}$, and then determining all other k- shortest paths. It is assumed that the container **A** will hold the k-shortest path, whereas the container **B** will hold the potential k- shortest paths. To determine $\mathbf{A^{1,}}$ the shortest path from the source to the sink, any efficient shortest path algorithm can be used.

To find the $\mathbf{A^k}$, where k ranges from 2 to k, the algorithm assumes that all paths from $\mathbf{A^1}$ to $\mathbf{A^{k-1}}$ have previously been found. The k iteration can be divided into two processes, finding all the deviations $\mathbf{A^k i}$ and choosing a minimum length path to become $\mathbf{A^k}$. Note that in this iteration, i ranges from **1** to $\mathbf{Q^k k}$.

| Notation | Description |
|---|---|
| **N** | The size of the graph,i.e the number of the nodes in the network |
| **(i)** | The $i^{th}$ node of the graph, where i ranges from 1 to N. |
| **$D_{ij}$** | The cost of the edge between (i) & (j), (i) /= (j) |
| **$A^k$** | The $K^{th}$ shortest path from (1) to (N), where k ranges from 1 to K. $A^k = (1) – (2^k) – (3^k) – …- (Q^k k) – (N)$ |
| **$A^k i$** | A deviation path from $A^{k-1}$ node $(i^k)$, where i ranges from 1 to $Q_k$ |
| **$R^k_i$** | The root path of $A^k_i$ that follows $A^{k-1}$ until the $i^{th}$ node of $A^{k-1}$. |
| **$S^k_i$** | The spur path of $A^k$ that starts at the $i^{th}$ node of the $A^k_i$ and ends at the sink. |

Table 2 : Terminology and notation for Yen's algorithm. [16]

The first process can be further subdivided into three operations, choosing the $\mathbf{R^k}$, finding $\mathbf{S^k_i}$ , and then adding $\mathbf{A^k_i}$ to the container B. The root path, $\mathbf{R^k_i}$ , is chosen by finding the subpath in $\mathbf{A^{k-1}}$ that follows the first i nodes of $\mathbf{A^j}$, where j ranges from **1** to **k-1**. Then, if a path is found, the cost of edge $\mathbf{d_{i(i+1)}}$ of $\mathbf{A^j}$ is set to infinity. Next, the spur path, $\mathbf{S^k_i}$, is found by computing the shortest path from the spur node, node i, to the sink. The removal of previous used edges from **(i)** to **(i+1)** ensures that the spur path is different. $\mathbf{A^k_i = R^k_i + S^k_i}$, the addition of the root path and the spur path, is added to B. Next, the edges that were removed, i.e. had their cost set to infinity, are restored to their initial values.

The second process determines a suitable path for $\mathbf{A^k}$ by finding the path in container B with the lowest cost. This path is removed from container B and inserted into container A and the algorithm continues to the next iteration. Note that if the number of paths in container B equal or exceed the number of k-shortest paths that still need to be found, then the necessary paths of container B are added to container A and the algorithm is finished.

There are two key features of Yen's algorithm, one is space complexity and another one is time complexity. To store the edges of the graph, the shortest path list A, the potential shortest path list **B,** $\mathbf{N^2 + KN}$ memory addresses are required. At worst case, every node in the graph has an edge to every other node in the graph, thus $\mathbf{N^2}$ addresses are needed. Only **KN** addresses are need for both list A and B because at most only K paths will be stored, where it is possible for each path to have nodes. The time complexity of Yen's algorithm is dependent on the shortest path algorithm used in the computation of the spur paths, so the Dijkstra algorithm is assumed. Dijkstra's algorithm has a worse case time complexity of **O($N^2$)** but using a Fibonacci heap it becomes **O (M+N log N),** where M is the amount of edges in the graph. Since Yen's algorithm makes **Kl** calls to the Dijkstra in computing the spur paths, where **l** is the length of spur paths. In a condensed graph, the expected value of l is **O (log N),** while the worst case is N, the time complexity becomes **O (KN (M+N\log N))**

### 3.2.3 Edge disjoint shortest pair algorithm (Bhandari algorithm)

The algorithm is used for generating the shortest pair of edge disjoint paths between a given pair of vertices as follows:
Run the shortest path Algorithm for the given pair of vertices. Replace each Edge of the shortest path (equivalent to the oppositely directed arcs) by a single arc directed towards the source vertex. Make the length of each of the above arcs negative. Run the shortest path Algorithm (Note: The Algorithm should accept negative costs). Erase the overlapping edges of the two paths found and reverse the direction of the remaining arcs on the first shortest path such that each arc on it is directed towards the sink vertex now. The desired pair of paths results.

G = (V, E) d(i) – the distance of vertex i (i∈V) from source vertex A; it's the sum of arcs in a possible path from vertex A to vertex i. Note that d(A)=0; P(i) – the predecessor of vertex I on the same path. Z – the destination vertex.

| | |
|---|---|
| Step 1 | Start with d(A)=0,<br>d(i) = l (Ai),<br>if i ∈ ΓA;<br>Γi ≡ set of neighbor vertices of vertex i,<br>l(ij) = length of arc from vertex i to vertex j = ∞,<br>otherwise (∞ is an enormous number defined below);<br>Assign S = V-{A}, where V is the set of vertices in the graph.<br>Assign P(i) = A, ∀i∈S. |
| Step 2 | a) Find j∈S such that<br>(j) = min d(i), i∈S.<br>b) Set S = S – {j}. |

| | |
|---|---|
| | c) If j = Z (the destination vertex) END;<br>otherwise go to Step 3 |
| Step 3 | ∀i∈Γj,<br>if d(j)+l(ij)<d(i),<br>a) set d(i) = d(j) + l(ij),<br>P(i) = j.<br>b) S = S ∪{i}<br>Go to Step 2. |

Table 3 : pseudo code of Bhandari algorithm (Edge disjoint shortest pair algorithm)

## 3.3 Spectrum Allocation

This section presents the spectrum allocation of the connection request. We introduce a first-last-exact fit allocation policy to separate the disjoint and non-disjoint connections. The first-last-exact fit allocation policy is a combination of two allocation policies, namely, (1) first-exact fit and (2) last-exact fit. The first-exact fit allocation policy is performed on connection whose paths belong to the non-disjoint connection group. The last-exact fit allocation policy is performed on connection whose paths belong to the non-disjoint connection group. These two allocation policies are expected to prevent small contiguous available slots that might be difficult to use for future connection request. Each of the allocation policy is explained in the following subsections.

### 3.3.1 First Fit Algorithm

In this scheme, all wavelengths are numbered. When searching for available wavelengths, a lower numbered wavelength is considered before a higher-numbered wavelength. The first available wavelength is then selected. This scheme requires no global information. Compared to Random wavelength assignment, the computation cost of this scheme is lower because there is no need to search the entire wavelength space for each route. The idea behind this scheme is to pack all the in-use wavelengths toward the lower end of the wavelength space so that continuous longer paths toward the higher end of the wavelength space will have a higher probability of being available. This scheme performs well in terms of blocking probability and fairness and is preferred in practice because of its small computational overhead and low complexity. Like Random, FF does not introduce any communication overhead because no global knowledge is required.

In the first fit algorithm, the allocator keeps a list of free blocks (known as the free list) and, on receiving a request for memory, scans along the list for the first block that is large enough to satisfy the request. If the chosen block is significantly larger than that requested, then it is usually split, and the remainder added to the list as another free block.

The first fit algorithm performs reasonably well, as it ensures that allocations are quick. When recycling free blocks, there is a choice as to where to add the blocks to the free list—effectively in what order the free list is kept.

| **Algorithm for allocate (n)** | |
|---|---|
| Step 1 | size(block) = n + size(header) |
| Step 2 | Scan free list for first block with nWords >= size(block) |
| Step 3 | **If** block not found<br>Failure (time for garbage collection!) |
| Step 4 | **Else if** free block nWords >= size(block) + threshold* |
| Step 5 | Split into a free block and an in-use block |
| Step 6 | Free block nWords = Free block nWords - size(block)<br>In-use block nWords = size(block) |
| Step 7 | **Return** pointer to in-use block |
| Step 8 | **Else**<br>Unlink block from free list |
| Step 9 | **Return** pointer to block |

Table 4 : First Fit Algorithm Allocation policy.

### 3.3.2 First-exact fit allocation policy

The first-exact fit allocation policy chooses the lowest indexed slot from the list of available slots that the number of available contiguous slots exactly same with the number of slot demand If there are no exact available contiguous slots, this policy allocates spectrum slots from the lowest indexed available slots. This technique is like the conventional first fit allocation policy except that it attempts to search the exact available contiguous slots at first. The details of the first-exact fit allocation policy are given in algorithm.

| First-Exact Fit allocation | |
|---|---|
| Input: | Disjoint connection request. |
| Output: | spectrum allocation |
| Step 1: | check the slot demand. |
| Step 2: | search the required available slots from the **smallest indexed slot**. If contiguous available slots **equal to** the slot demand are found. Go to step 4. Otherwise, go to step 3. |
| Step 3: | search the required available slots from the **smallest indexed slot**. If contiguous available slots **larger than** the slot demand are found. Go to step 4. Otherwise, go to step 5. |
| Step 4: | Allocate the contiguous available slots. |
| Step 5: | Reject the connection request. |

Table 5 : First Exact Fit Algorithm Allocation Policy.

### 3.3.3 Last-exact fit allocation policy

The last exact fit allocation policy chooses the highest indexed slot from the list of available slots that have the number of available contiguous slots exactly same with the number of slot demand. If there are no exact contiguous available slots, this policy allocates spectrum slots from the highest indexed slot from the list of available slots. The details of the last-exact fit allocation policy are described below. The time complexity of this algorithm is , which is mainly required to perform spectral allocation for Z connection request using given route.

| Last-Exact Fit allocation | |
|---|---|
| Input: | Disjoint connection request. |
| Output: | spectrum allocation |
| Step 1: | check the slot demand. |
| Step 2: | search the required available slots from the **highest indexed slot**. If contiguous available slots **equal to** the slot demand are found. Go to step 4. Otherwise, go to step 3. |

| | |
|---|---|
| Step 3: | search the required available slots from the **highest indexed slot**. If contiguous available slots **larger than** the slot demand are found. Go to step 4. Otherwise, go to step 5. |
| Step 4: | Allocate the contiguous available slots. |
| Step 5: | Reject the connection request. |

Table 6 : Last Exact Fit Algorithm Allocation Policy.

Here in Figure 25 , explains an example of the advantage of exact fit, which can be applied to both first-exact and last-exact fit policies. In this Figure 25(a) shows a condition of the subcarrier slots, where slots 1,2,3, 5 and 6 are available at link 2. When a connection (using link 2) with two slots demand arrives, its slots are allocated differently depending on the allocation policy. If we use the first fit allocation policy, slots 1 and 2 are allocated, as shown in Figure 25(b). In this case, if any future connection request arrives with three slot demands, it cannot be established due to the lack of contiguous available slots. However, if we use the first-exact fit policy, as shown in figure, the future connection request with three slot demands can be established.

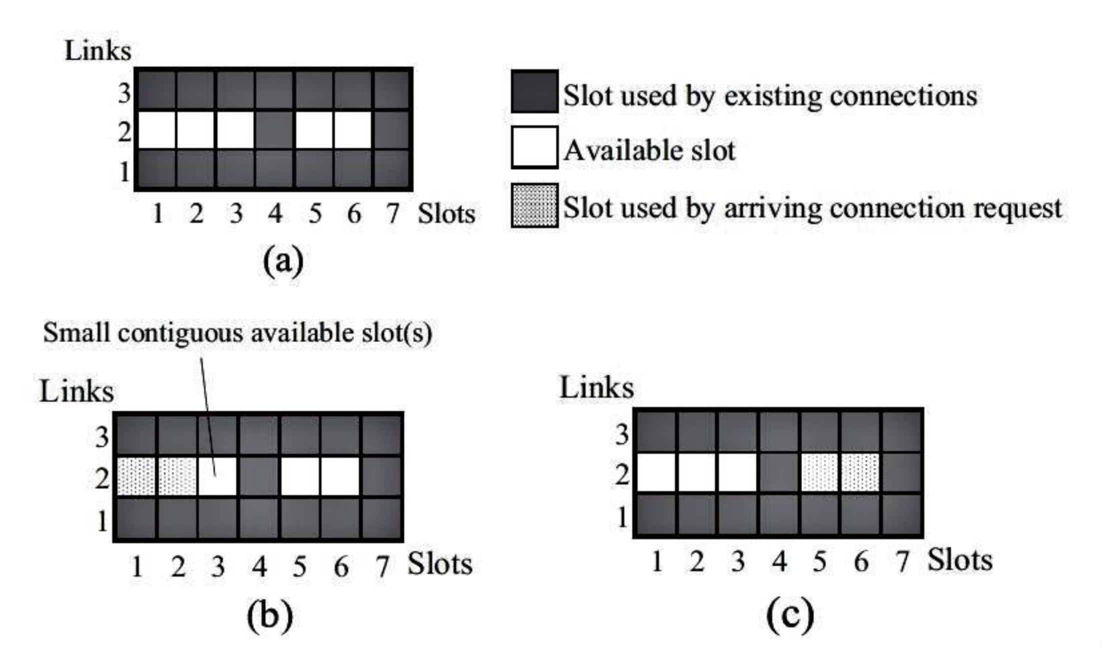



Figure 25 : (a) Network subcarrier slot initial condition, and spectrum allocation using (b) first fit and (c) first-exact fit policies.

## 3.4 Routing and wavelength/spectrum assignment (RWA, RSA)

Routing and spectrum assignment (RSA) is considered one of the key functionalities due to its information transparency and spectrum reuse characteristics. RSA is used to (i) find the appropriate route for a source and destination pair, and (ii) allocate suitable spectrum slots to the requested lightpaths.

The RSA problem in elastic optical networks is equivalent to the RWA problem in WDM-based optical networks. The problem of establishing lightpaths for each connection request by selecting an appropriate route and assigning the required wavelength is known as the routing and wavelength assignment (RWA) problem. In WDM-based optical networks without wavelength converters, the same wavelength must be used on all hops in the end-to-end path of a connection. This property is known as the wavelength continuity constraint. The difference of RSA and RWA is due to the capability of the elastic optical network architecture to offer flexible spectrum allocation to meet the requested data rates. In RSA, a set of contiguous spectrum slots is allocated to a connection instead of the wavelength set by RWA in fixed-grid WDM based networks. These allocated spectrum slots must be placed near to each other to satisfy the spectrum contiguity constraint. If enough contiguous slots are not available along the desired path, the connection can be broken up into small multiple demands. Each one of these smaller demands would then require a lower number of contiguous subcarrier slots. Furthermore, the continuity of these spectrum slots should be guaranteed in an analogous manner as demanded by the wavelength continuity constraint. If a demand requires t units of spectrum, then t contiguous subcarrier slots must be allocated to it (due to the spectrum contiguity constraint), and the same t contiguous slots must be allocated on each link along the route of the demand (due to the spectrum continuity constraint).

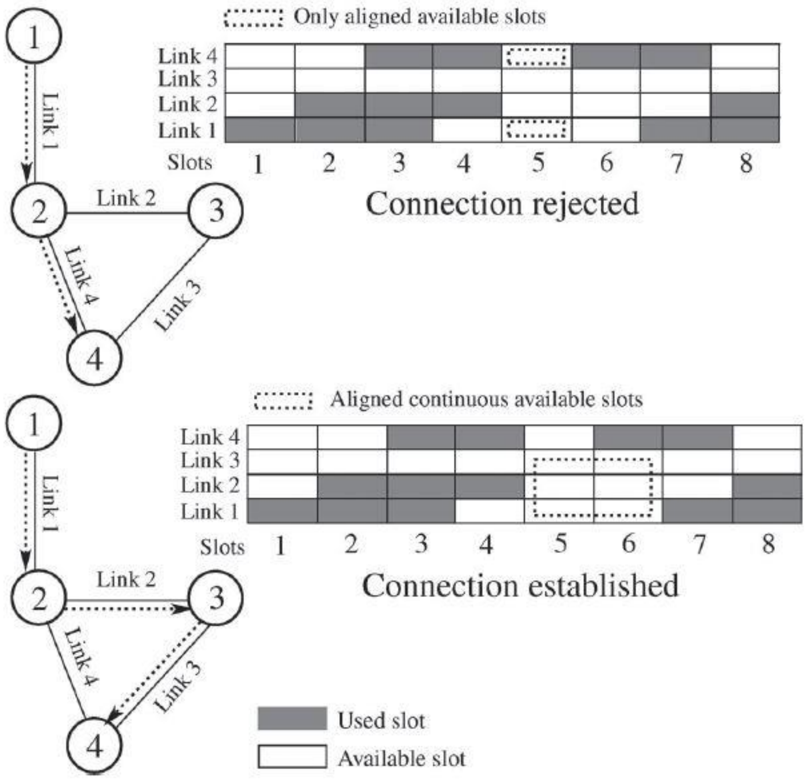



Figure 26 : Example of continuity and contiguity constraints. [14]

The concept of the contiguity and continuity constraints of the spectrum allocation is explained with an example. For this purpose, we consider the network segment shown in Figure 26.We assume a connection request that requires a bit-rate equivalent to two slots for RSA from source node 1 to destination node 4. The connection request cannot be established through the shortest route 1-2-4 because the links from 1-2 and 2-4 have two contiguous slots that are not continuous, so the continuity and contiguity constraints are not satisfied. However, the continuity and contiguity constraints are satisfied if the connection uses the route 1-2-3-4, and spectrum slots 5 and 6. RWA in WDM-based optical networks is an NP-hard (Nondeterministic polynomial time) problem and has been well studied over the last twenty years. The RWA problem is reducible to the RSA problem as the number of wavelengths equals the number of spectrum slots in each fiber link. For any lightpath request, if RWA requires 1 wavelength along the lightpath, it is equivalent to a 1 spectrum slot request along the lightpath in the RSA problem. This reduction is within poly-nominal time. The RWA problem has a solution if and only if the constructed RSA problem has a solution. Therefore, from the above discussion, we can say that the RSA problem is an NP-hard problem. Although RSA is a hard problem, it can have simplified by splitting it into two separate subproblems, namely (i) the routing subproblem, and (ii) the spectrum allocation subproblem.

## 3.5 Regenerator Placement

In optical networks, the optical reach is defined as the distance an optical signal can travel, before its quality degrades to a level that requires 3R-regeneration (Re-amplification, Re-shaping, Re-timing). In a translucent optical network, if an optical signal must be communicated over a distance that exceeds the optical reach, the signal is regenerated at selected nodes of the network, so that the signal quality never degrades to an unacceptable level. Given a value of the optical reach, the goal of the Regenerator Placement Problem (RPP) in dynamic Physical Impairment Aware Route and Wavelength Assignment (PI-RWA) , for survivable translucent networks, is to identify the minimum number of nodes capable of 3R regeneration, so that every pair of nodes (u, v) can establish a lightpath (either transparent or translucent) from u to v. In a survivable network, even if any fault occurs, it must be guaranteed that every pair of surviving nodes (u, v) can still establish a lightpath (either transparent or translucent) from u to v, avoiding all faulty nodes/edges. I have presented an Integer Linear Program (ILP) formulation that can optimally solve the survivable RPP problem for practical-sized networks within a reasonable amount of time shown in Figure 27. Using branch-and-cut technique to implement the algorithm, where I have intercepted the optimization process with control callbacks from the CPLEX callable library to introduce new constraints, as needed.

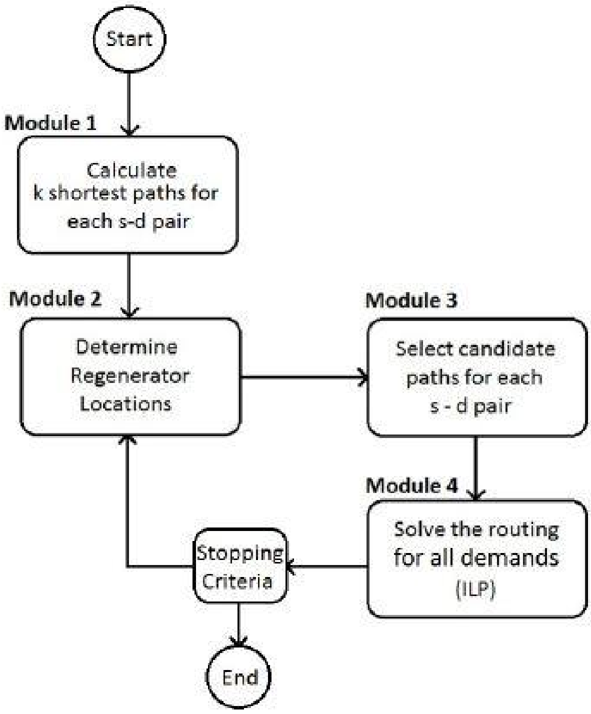



Figure 27 : Flow chart of Tabu search-based Regenerator Placement Algorithm. [15]

### 3.5.1 Problem of Regenerator placement for wavelength impairment

Regenerator placement in elastic optical networks with adaptive modulation and coding (AMC) can be explained. AMC profile in elastic optical networks (EON) is studied to propose an offline RP algorithm for a given network topology with link length and link capacity constraints. Using this technique, the slices assigned for each demand are utilized efficiently with different modulation and coding rates, namely AMC profiles. Given the topology information (nodes, links, link capacity and set of AMC profiles) and the demand set (source-destination nodes and demanded bit rates), find the nodes to be placed with regenerators such that: [15]

- Primarily, the number of regenerator node is minimized.
- The total utilized link capacity is minimized based on the selected regenerator locations.
- All requested demands are satisfied.
- Appropriate AMC profile are selcted for each demand such that máximum reach constraint is satisfied and sufficient number of slices are allocated.
- Link capacities are not violated.

To propose a solution to the growing heterogeneous traffic demand, the development of EONs enabled the utilization of spectrum sources more flexibly. In addition to the flexible bandwidth utilization, the capabilities of the 3R regenerator are increased compared to the ones used in WDM networks. According to the optical reach needed for a transmission, the 3R regenerators of EON can adjust the modulation and code rate without any spectrum limitation of fixed grid. Transmission techniques like TFP (Time frequency packets) increased spectral efficiency and robustness against physical impairments.

| **Adaptive Modulation and Coding (AMC) profile** | **Code rate** | **Reach [km]** | **BW [GHz]** | **Subcarrier #** | **Slice #** |
|---|---|---|---|---|---|
| 1 | 9/10 | 3000 | 196 | 7 | 16 |
| 2 | 5/6 | 4000 | 224 | 8 | 18 |
| 3 | 3/4 | 5000 | 252 | 9 | 21 |

Table 7 : set of reachability and spectral efficiency required for 1Tb/s with different LDPC code rates. [15]

In other words, each slice on a link can be assigned with an AMC profile, which corresponds to spectral efficiency and reachability metric. In Table 7, different code rates are presented which are used as AMC profiles.

# 4 Fragmentation metrics and their use in allocation algorithm

There are two main objectives of this section. One is to understand if and how much could be important to apply fragmentation indexes in spectrum allocation algorithms, if the final goal is to maximize the whole carried traffic and minimize the percentage of blocking on a link or in a network. Another objective is to see the use of the metrics in the allocation algorithm and Evaluation of fragmentation metrics.

## *4.1 Spectrum Fragmentation problem in optical network*

Spectrum Fragmentation (SF) includes sub-optimal (Moderate standard) spectrum distribution that causes unusual block of the incoming connection demands, even when there are enough spectral resources scattered in the network.

Fragmentation is recognized as a detrimental condition for an efficient use of optical resources, since available slots are isolated from each other by being misaligned/discontinuous along the routing path or non-contiguous in the spectrum domain in a single link thus, in a fragmented network, the available free spectrum cannot be used to allocate a new demand which is considered as rejected or blocked, and the isolated free slots cannot be used to accommodate traffic.

### 4.1.1 Vertical and Horizontal Spectrum Fragmentation

The acceptance of the optical connection on links and networks depend on two types of fragmentation. Each type is deriving from a specific constraint in the demand allocation.
Firstly, considering for not having fragmentation spectrum on a single link, all free slots must be contiguous. But, in general, the free spectrum on a link is not compact and not able to allocate new demand. There must be as many free contiguous slots as demand requires. If this condition is not satisfied the incoming demand will be blocked by the so called vertical fragmentation (VF) issue.
Secondly, Spectrum continuity on a path (set of links used to route and allocate an incoming demand in a transparent network) the set of links must respect the wavelength continuity. If this condition is not satisfied the incoming demands types will be blocking by Horizontal Fragmentation (HF) issue.

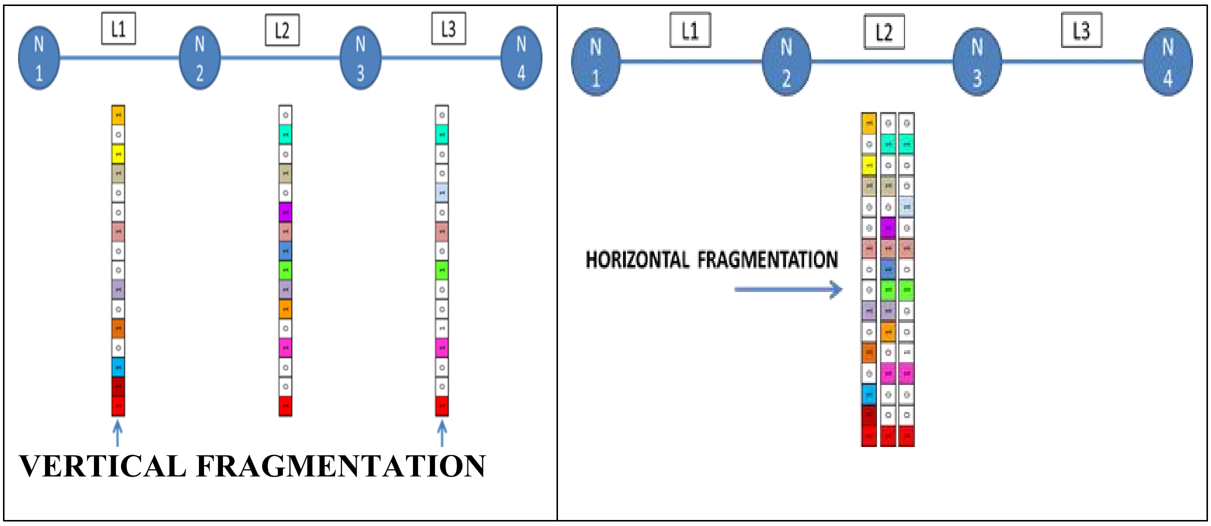



Figure 28 : Vertical and horizontal fragmentation in a path of 4 nodes and set links with 16 usable slots. [22]

### 4.1.2 Vertical and Horizontal Fragmentation in Fixed and Flex grid

Now, we will see the concepts of spectrum fragmentation and congestion by means of examples. In Figure 29 (a) a demand (I. e. an optical circuit) needing 3 spectrum slots is required to be allocated on a link of 12 spectrum slots whose occupation pattern is highlighted with white (free slot) and red (busy slot) squares. In this case the demand is blocked for resource congestion as the free slots are less than the slots needed by the demand. In Figure 29(b) the same demand is offered to a link whose occupation pattern shows a total 6 free slots, but with a contiguous free slot blocks of a maximum of two slots: the demand is blocked also in this case. The condition of Figure 29(b) is known as vertical fragmentation (VF) of the spectrum and involves each link individually. Figure 29(c) shows a path of three links in a network whose it is offered once again a demand of 3 slots. Each link separately could accept the demand but, due to the spectrum continuity requirement from source to destination, the demand is blocked. This kind of fragmentation, present only in networks, is called horizontal fragmentation (HF). Blocking for congestion involves both fixed grid and flexible grid networks. Blocking for vertical fragmentation is present only in flexible grid networks while blocking for horizontal fragmentation is present in both fix grid and flexible grid network. It's worth noting that HF can be solved at the expense of regeneration (i. e. spectrum shifting by optical electro optical (OEO) conversion) in the intermediate nodes of the path.

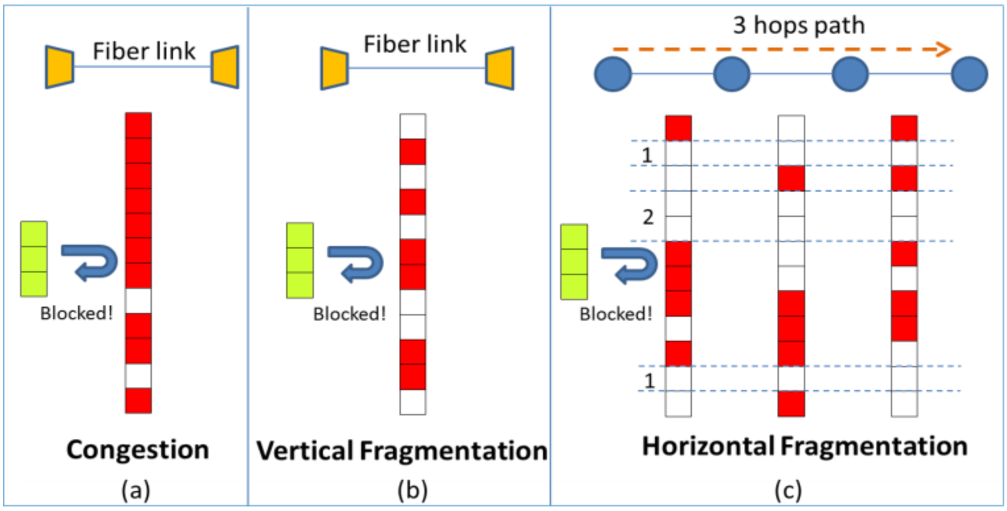



Figure 29 : Causes of blocking in the link and in the network. [22]

## 4.2 *Overview of fragmentation metrics*

Before it became an issue in optical networks, the fragmentation problem was extensively studied and analyzed in the field of computer memory management. In general, fragmentation metrics in optical networks have the aim to measure the degree of the order with which a resource (typically a link but also, for extension, a whole network) is used or, according to an alternative view, to measure the resource accessibility to allocate future additional channels. Apart from its own general meaning and usefulness as a figure of merit of the rational use of resources, fragmentation metrics find applications in spectrum allocation algorithms and in defragmentation algorithms. In defragmentation algorithms they are used to pilot a reordering process (defragmentation) of network resource when the spectrum is recognized as highly fragmented and to prevent the refusal of additional channel requests.

Based on some main characteristics, three main classes of metrics have been identified. A first class of fragmentation metrics encompasses the ones for which the metric value depends only on the slice occupancy pattern of the link state under consideration. A second class includes metrics in which values depend on both the slice occupation pattern and on all the types of traffic which load the resource. Both these two first classes of metrics give one value of the fragmentation index for each possible state of slice occupancy pattern. A third class is characterized by values of the metric which are specific for each granularity to be allocated. Metrics belonging to this third class are characterized by a vector of values (one value per each granularity) for each slot occupancy pattern. These three classes introduced above do not depend on ongoing link occupancy transitions in a dynamic scenario, but only on the characteristic of a given state (typically a candidate next state if the metric was used in a spectrum allocation algorithm) and, for the second and third classes, also on the granularities involved.

| ***FRAGMENTATION METRICS*** | |
|---|---|
| **Class 1** | • Shannon Entropy (**SH** of three different types: free $(SE^{free})$, busy $(SE^{busy})$ and average $(SE^{aver})$<br>• Utilization Entropy (**UE**)<br>• External Fragmentation (**EF**)<br>• Spectrum compactness (**SC**)<br>• High-slot-Mark (**HsM**) |
| **Class 2** | • Access Blocking Probability (**ABP**) |
| **Class 3** | • Vectorial Fragmentation (**VF1**) |

Table 8 : Classification of Fragmentation metrics.

The following notation is the reference one throughout all this work and it standardizes the representation of all the analyzed spectrum fragmentation metrics.

- $Ls$ : Number of usable spectrum slots in an optical link
- $s\ (i),\ i = 1\ \dots Ls$ : slot status (0 = free or 1 = busy).
- $S_f^f ree$: Size of free fragment *f*.
- $N_F$ : Number of free fragment in a link.
- $S_f^b usy$: Size of busy fragment *f*.
- $N_B$ : Number of busy fragments in a link.
- $G_g$ : Size in slot of spectrum required to allocate a demand of type *g*.
- $N_G$ : Number of demand types (i.e. demands which require different spectrum size).
- $i_{min}^{busy}$, $i_{max}^{busy}$: Indexes of first (min) and last (max) busy slot in a link.
- $K^c omp$: Number of free fragments between the first and the last busy slot in a link.

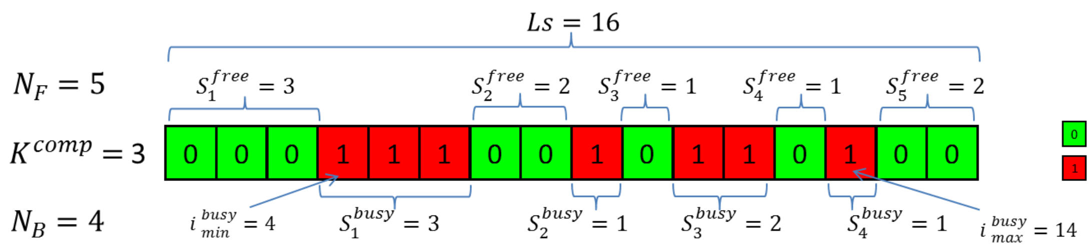



Figure 30 : Single optical link with common notation. [22]

The red and green colors, and the binary code 1 and 0, indicate whether a spectrum slot is currently used or unused, respectively. Please note that, with this representation only the slot occupancy on the link is represented. While it does not give indication about which connection type engages the occupied spectrum (i.e. how many slots are individually by the allocated connections).

- **Shannon Entropy (SE)**

Shannon entropy of an optical link can be defined in three alternative ways. The first one, named Shannon entropy free $(SE^{free})$, evaluates the fragmentation considering only the blocks of free spectrum. The second type of Shannon entropy applied to an optical link is named Shannon entropy busy $(SE^{busy})$ and it is defined in a similar way with the difference that it uses busies spectrum blocks instead of the free ones. The third and last type of Shannon Entropy, which is identified by Shannon entropy average ( $SE^{aver}$ )is defined as the average between the first two type. [24]

- **Utilization Entropy (UE)**

It is a metric to indicate the level of fragmentation in optical network. Unlike conventional capacity-based parameters (such as link utilization, network load, etc. which measure how much resources are used), UE measures how well a resource is used in terms of slot occupancy transitions: the more are the slot occupancy transitions the higher is this kind of entropy. Practically UE is calculated looking the number of state changes in slot occupation: the higher the changes, the higher the fragmentation level. [25]

- **External Fragmentation (EF)**

External Fragmentation (EF) measures the state of fragmentation having as a reference the ratio between the size of the maximum free block and the total amount of free spectrum $N_F$. It was originally proposed in for computer memory and then applied as a measure of spectrum fragmentation in optical links. [27]

- **Spectrum Compactness (SC)**

Spectrum Compactness (SC) is a fragmentation index defined in with the aim to describe the occupation of spectrum fragments in a link or in the network. This fragmentation index measures the compactness of the spectrum between the first and the last busy slot. Spectrum is maximally compact. [26]

- **High slot Mark (HsM)**

High slot Mark is an indicator of the portion of the spectrum that is surely free and unfragmented in a link or in a network. Particularly, HsM is defined as the right most (or left-most, in that case such index should be called Low-slot Mark (LSM)) used slot identifier number of the link. HsM has been proposed to be essentially used in synergy with First Fit (FF) spectrum allocation criterion where, if the FF allocates a connection on the left-most (right-most) suitable free portion of the spectrum, HSM (LSM) records the right-most (left-most) used slot of the link spectrum. [19]

- **Access Blocking Probability (ABP)**

A fragmentation metric named Access Blocking Probability (ABP) is proposed with the characteristic of the demand in presence of multi-granular connection types. ABP calculates the ratio between the sum of the cardinalities (i.e. number of occurrences) of the all demand's granularities that can be used in every free fragment $S_f^f ree$, and the sum of cardinalities of the demand's granularities that can be allocated if all free slots would take part of single contiguous block. The lower is such ratio, the higher is assumed to be the probability for a new demand to be rejected for spectrum fragmentation of the link. In fact, when the link is un-fragmented the above ratio is 1, this means that the link is not congested, while the ratio reaches the value 0 when the link fragmentation level does not allow the allocation of connections of the smallest granularity, the ratio is 0. When the link is totally congested, (i.e. the total free slots are not sufficient to allocate even the smallest granularity) the above-mentioned rate cannot be calculated and the value 1 is assigned by default to the PB metric. [19]

| Metric | Equation |
| --- | --- |
| **High-slot Mark (HSM)** | $\overline{HSM} = \frac{i_{max}^{busy}}{L_S}$ |
| **Utilization Entropy (UE)** | $UE = \frac{X_s}{L_s - 1}, X_s = \sum_{i=1}^{L_s-1} xor(s(i), s(i+1))$ |
| **Shannon Entropy(SE)** | $SE^{free} = \sum_{f=1}^{N_F} \frac{S_f^{free}}{L_s} \ln \frac{L_s}{S_f^{free}}$ <br> $SE^{aver} = \frac{SE^{free} + SE^{busy}}{2}$ |
| **External Fragmentation (EF)** | $EF = 1 - \frac{\max_f\{S_f^{free}\}}{\sum_{f=1}^{N_F} S_f^{free}}$ |
| **Spectrum Compactness (SC)** | $SC = \frac{i_{max}^{busy} - i_{min}^{busy} + 1}{\sum_{f=1}^{N_B} S_f^{Busy}} * \frac{1}{K^{comp}}\ for\ K^{comp} \geq 1$ |
| **Access Blocking Probability (ABP)** | $ABP = 1 - \frac{\sum_{f=1}^{N_F}[\sum_{g=1}^{N_G}(S_f^{free}\ DIV\ G_g)]}{\sum_{g=1}^{N_G}\left[\left(\sum_{f=1}^{N_F} S_f^{free}\right) DIV\ G_g\right]}$ |

Table 9 : Summary of metrics formulas without normalization.

The different link-oriented fragmentation metrics are summarized in this table. The external fragmentation metric has the lowest time complexity of all considered metrics as it inspects only the largest block. It recognizes that there is no fragmentation effect if all free slots are contiguous. In this case, the maximum number of available contiguous slots is equivalent to the number of slots in the link, which indicates the initial condition of the link. The disadvantage of the external fragmentation metric is that it ignores the small fragments to focus on the maximum number of available contiguous slots in the link. Like the external fragmentation metric, the entropy-based fragmentation metric is unable to distinguish the case when fragmented slots match the available granularities from the inappropriate fragmented cases. This metric can efficiently estimate relative fragmentation, and so allows comparisons of different arrangements. The complexity of the entropy-based fragmentation metric is linear to the number of fragments. The access blocking probability metric can estimate fragmentation more comprehensively than the previous two metrics. When all fragments are smaller than the smallest granularity, the access blocking probability metric finds that the spectrum is completely fragmented. If the spectrum is not fragmented, it returns zero, which indicates that all slots are free and contiguous. As the access blocking probability metric returns a relative value between zero and one, it can also be used to compare relative levels of fragmentation; the more the spectrum is fragmented, the greater relative fragmentation is. However, like the external fragmentation metric, the access blocking probability metric cannot differentiate whether all slots are free, all slots are used, and all free slots are contiguous. This metric has higher time complexity than the other metrics considered here.

| Fragmentation Metrics | Complexity of Computational time | Observation and Comments |
|---|---|---|
| High Slot Mark | Very low | Useful only on association with First Fit allocation criteria |
| Utilization Entropy | Low | It doesn’t mind at size of free blocks, but only to transitions between free and busy slots. This means that two links with the same UE value can have different behavior in term of acceptance for new connections. |
| External Fragmentation | Low | It ignores the small fragments as it focuses on the maximum number of available contiguous slots in the link. |
| Shannon Entropy | Moderate | It considers any fragmented block (free slots, busy slots or both) and estimates relative fragmentation. |
| Spectrum Compactness | Moderate | Measure the compactness of the spectrum between the first and the last busy slots. |
| Access blocking probability | High | It deals with available granularities and tries to avoid situation where these granularities are blocked. |

Table 10 : Summarization of different link-oriented fragmentation metrics.

## 4.3 Spectrum allocation algorithm based on fragmentation metrics

The aim of the spectrum allocation algorithm to decide where to allocate a new demand request if enough free contiguous slots of the spectrum are available on the current state of the link (i.e. if at least one fragment of $G_g$ free slots or greater exists, where $G_g$ is the size of granularity of the demand). If there is not enough available spectrum to allocate the incoming demand, it is blocked (refused) and the next state is identical to the current state.

The spectrum allocation policies are classified in the three main classes: Random, current state based, and next state based. The Random state is the only one included in the first class: it doesn't use any information about the link occupation pattern and choses randomly the portion of spectrum on which allocate the demand. Random assignment is expected to have the worst performances in terms of allocation efficacy and it is introduced for benchmarking purpose. In the second class the allocation policy looks only at the current link occupancy state to decide where allocating the spectrum for the incoming demand and it is based on very simple rules (FF and exact fit) are the two taken in consideration). The third class relies on an algorithm which use the fragmentation metrics as allocation criterion. The allocation algorithm is the same for all fragmentation metrics and it is shown in Figure 31. This algorithm is based on the evaluation of the metric values of all the next link occupation states obtained by the allocation of the demand on all possible alternatives allowed by the free spectrum of the current state. The demand allocation is determined so that the resulting link occupancy (next state) is the one with the minimum metric value. In case of more minima, first fit is applied to them.

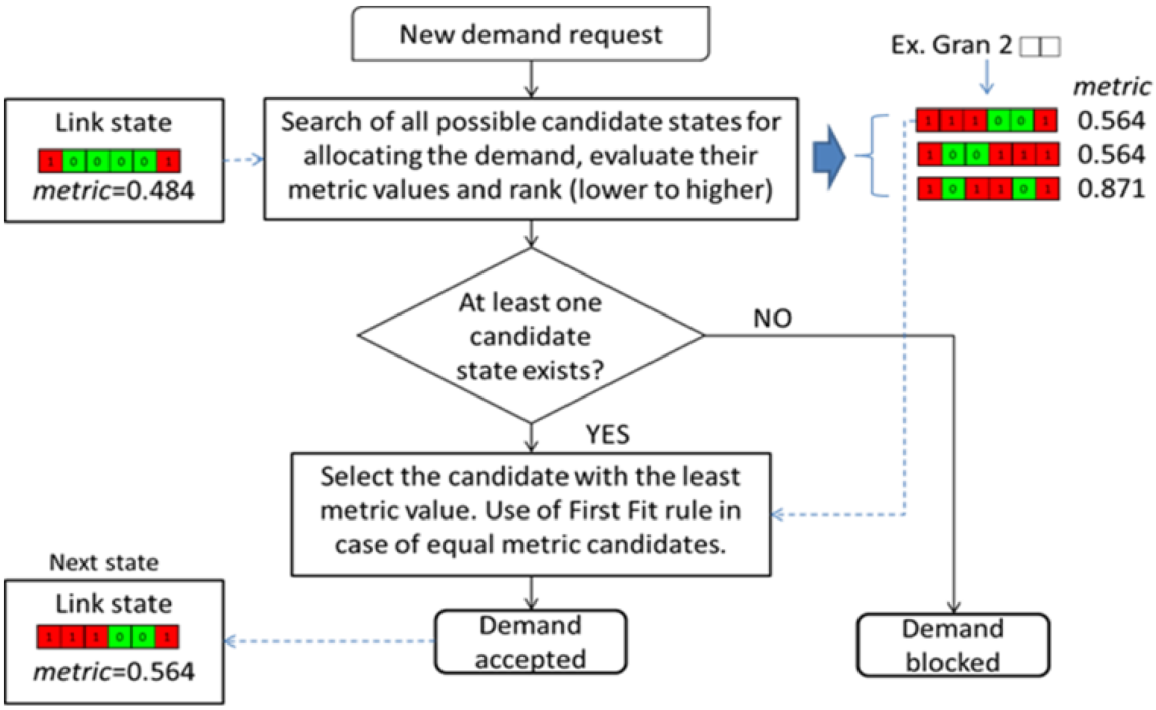



Figure 31 : Spectrum allocation algorithm. [19]

Following section presents spectrum allocation algorithm based on fragmentation metrics. Allocations based on a rule which depends on the property of the next state. Allocation based on fragmentation metrics is considered. The rule for the choice of the next state is the following one: the next state is the one among the complete set of candidate next states which have the lowest value of the fragmentation metric. In case of multiple candidates with the same lowest value of the metric, the first fit is applied as a secondary selection criterion.

- **Random Fit Algorithm Based On Fragmentation Metrics**

The random fit policy maintains a list of free spectrum slots. When a lightpath request arrives in the network, the policy arbitrarily chooses an available spectrum slot and uses it for lightpath provisioning. After slots are assigned, the list of free slots is refreshed by removing the just-assigned slot from the available list. Once a lightpath is released, the just-released slot is added to the list of free slots. By selecting spectrum slots in a random manner, the network operator tries to reduce the possibility that some specific spectrum slots are often used. In this case, allocated spectrum slots are uniformly distributed over entire spectra. [20]

- **Least Used Algorithm Based On Fragmentation Metrics**

The free spectrum slots, which have been utilized by the smallest number of fiber links in the network, are the focus of the least used spectrum allocation policy to satisfy lightpath requests. If several spectrum slot candidates are equally possible, the first fit spectrum allocation policy is used to select the best candidate. Choosing spectrum slots in this way attempts to distribute the load uniformly across the entire spectrum domain. [20]

- **Most Used Algorithm Based on Fragmentation Metrics**

The spectrum allocation of the most used policy is like that of the least used policy. Instead of choosing the spectrum resources that have been utilized by the least number of fiber links in the network, this policy selects free slots, which have been utilized by the most number of fiber links in the network. Choosing spectrum slots using this policy is an effort to enhance the reuse of spectrum in the network. [20]

Figure 32 Represents blocking probability vs traffic load considering different spectrum allocation policies. We can see from this figure that; random fit contains the higher blocking probability than other allocation policies. The other three (smallest fit, exact fit and first fit) allocation policies are showing same nature in blocking probability vs traffic load plot.

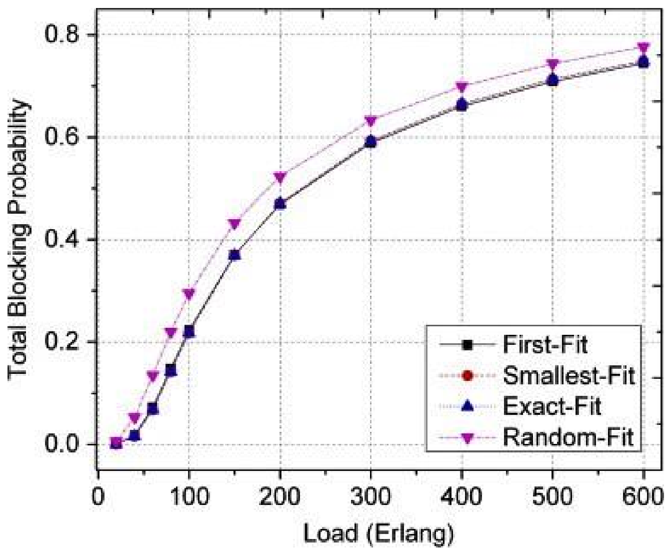



Figure 32 : Blocking probability vs Traffic load (Erlang) for different spectrum policies.

In Figure 33 condenses the major spectrum allocation policies. We compare the performance of these spectrum allocation policies in terms of contiguous aligned available slot ratio under varied traffic load. We estimate the relationship between the traffic load and the average slot utilization in NSFNET (The National Science Foundation Network). The assumption including lightpath request distribution and maximum number of occupied spectrum by lightpaths. By observing the literature, the least used and most used allocation policies have the highest time complexity. [20]

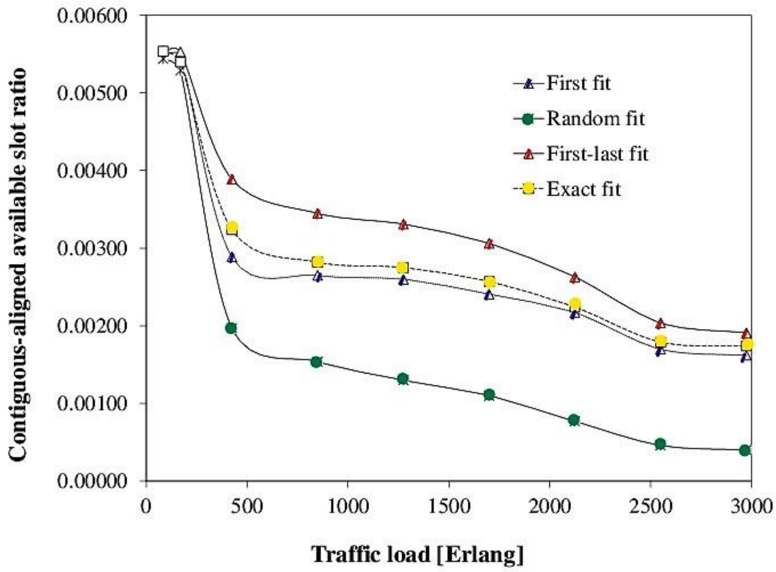



Figure 33 : Comparison of major spectrum allocation policies in terms of contiguous- aligned available slot ratio in NSFNET.

# 5 Defragmentation algorithms for elastic optical networks

In elastic optical networks (EONs), dynamic setup and release (tear down) of lightpaths will lead to spreading the optical spectrum into nonaligned, isolated and small sized spectrum blocks. As introduced in previous chapters, this issue is called spectrum fragmentation. Defragmentation strategies are key counter measures to minimize the problem of spectrum fragmentation. Defragmentation, implemented by algorithms and usually running as defragmentation engine in the control plane, is a process that attempts to reduces the amount of fragmentation with the aim to reduce the blocking of new connection attempt and therefore allowing a higher utilization of network resource.

## *5.1 Overview of Defragmentation techniques*

To understand the basic concept of Defragmentation technique some important definition such as call admission control (CAC), Defragmentation Engine (DE) and Fragmentation Index Computation Function (FICF) are introduced.

**CAC** is a function that evaluates any connection request and decide about its: i) acceptance in case of available resources, ii) put in standby in case of lack of resources and when it is evaluated that some actions on the network (i.e., defragmentation) can be made to reorganize the resources for making possible the connection acceptance, and iii) rejection when no actions on already established connections can make possible the new connection acceptance. For simplicity it is assumed that the CAC is centralized, and the connection requests are processed sequentially one at a time.

**DE** is a function that, once triggered, executes a defragmentation cycle which consist of a set of lightpath reallocations performed to reduce the fragmentation and as a consequence to enhance the network resource accessibility.

**FICF** is a function that computes asynchronously with respect to the connection request arrival process, the fragmentation level of the network (by means of a metric or in another way) and when a given threshold is exceeded a trigger command is generated for activating the defragmentation process.

### 5.1.1 Working principle of defragmentation algorithm

Generally, defragmentation algorithm can perform according to two strategies. The first one is called reactive and the second one is known as proactive. In Reactive strategy when a connection (lightpath) does not find resources, and network is not recognized as congested (i.e., an effective criterion is supposed to be available to identify the state of congestion), the connection is temporarily put in standby. and a defragmentation algorithm is activated. This approach can be seen in the left and center part of Figure 34.

In a typical proactive strategy when a trigger event is generated the network control is passed from the CAC to the DE. A specific algorithm searches for a set of established lightpaths that once reallocated (re-routed and/or shifted in frequency, i.e., reallocated in another portion of the spectrum) they free resources for the new connection request in standby. The identified lightpaths in the above step are reallocated one at a time when all the lightpaths are reallocated, the control is given back to the CAC. Then CAC tries to allocate the connection put in standby if new network status allows, resources allow the allocation of the waiting connection (as expected) the lightpath is established, otherwise it is rejected (in the last case, for some reasons, the defragmentation has not been effective). Then new connection requests can be evaluated by the CAC.

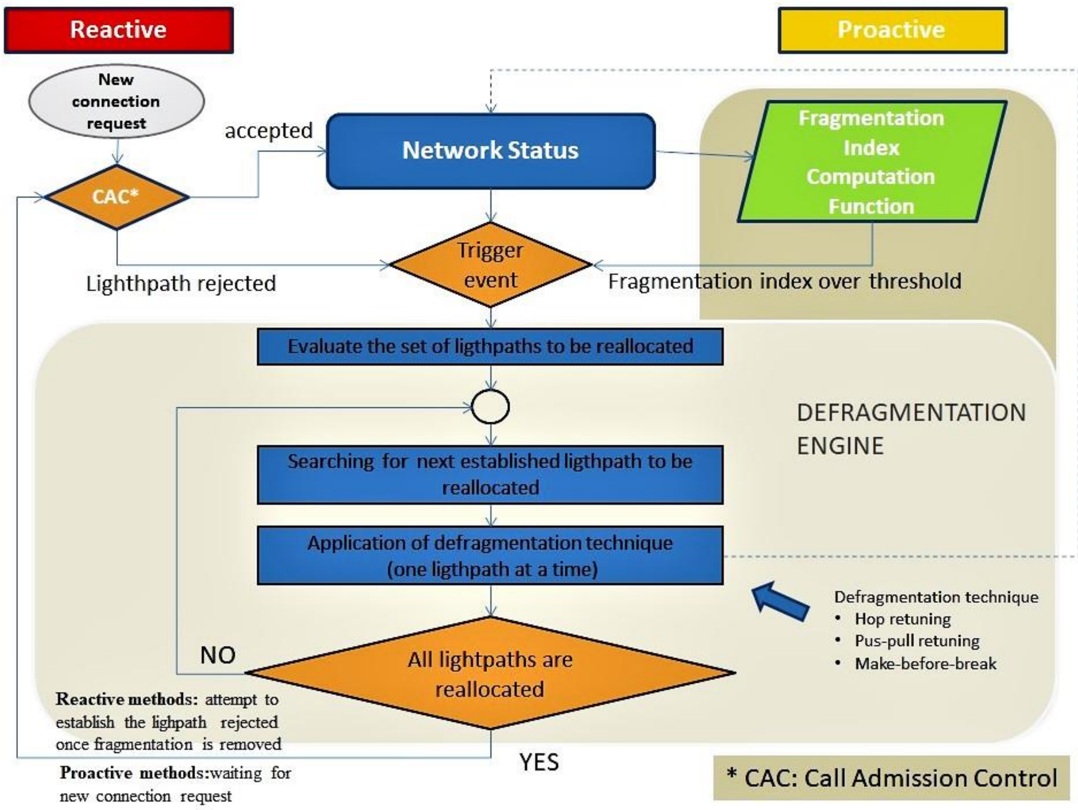



Figure 34 : standard structure of both reactive and proactive defragmentation strategy.

Concerning proactive methods, the way they work is shown in right and center part of Figure 34, The fragmentation index of the network is continuously updated by the FICF. This can be done at regular time periods independently on what happened just before or activated by special events that have changed the network resource occupancy status and, with a high probability, the level of spectrum fragmentation. Such special events are lightpath set up events and lightpath tear down events. In the presence of a such trigger event, the network control is passed from the CAC to the DE. A specific algorithm searches for a set of established lightpaths that can be reallocated to reduce the fragmentation. Then the identified lightpaths in the above step are then reallocated one at a time. When all the lightpaths are reallocated, the control is given back to the CAC and so new connection requests can be processed.

## 5.2 Classification of fragmentation management techniques

Fragmentation management techniques deal with spectrum fragmentation and increase the amount of traffic that can be accepted and carried by a network. Figure 35 shows the classification of fragmentation management techniques [20]. Basically, it focuses in two types, such as non-defragmentation and defragmentation techniques. Non-defragmentation and defragmentation approaches are not mutually exclusive and specific fragmentation management scheme can be implemented applying a synergy of both non-defragmentation and defragmentation approaches. In the Non-defragmentation techniques, preventive actions are taken to avoid fragmentation before the establishment of a lightpath, but no actions on already established connections are allowed. As far as concern defragmentation technique, a necessary action is taken about in-service lightpaths (e.g. rerouting or frequency shifting of lightpath) to reduce degree of the fragmentation of the network.

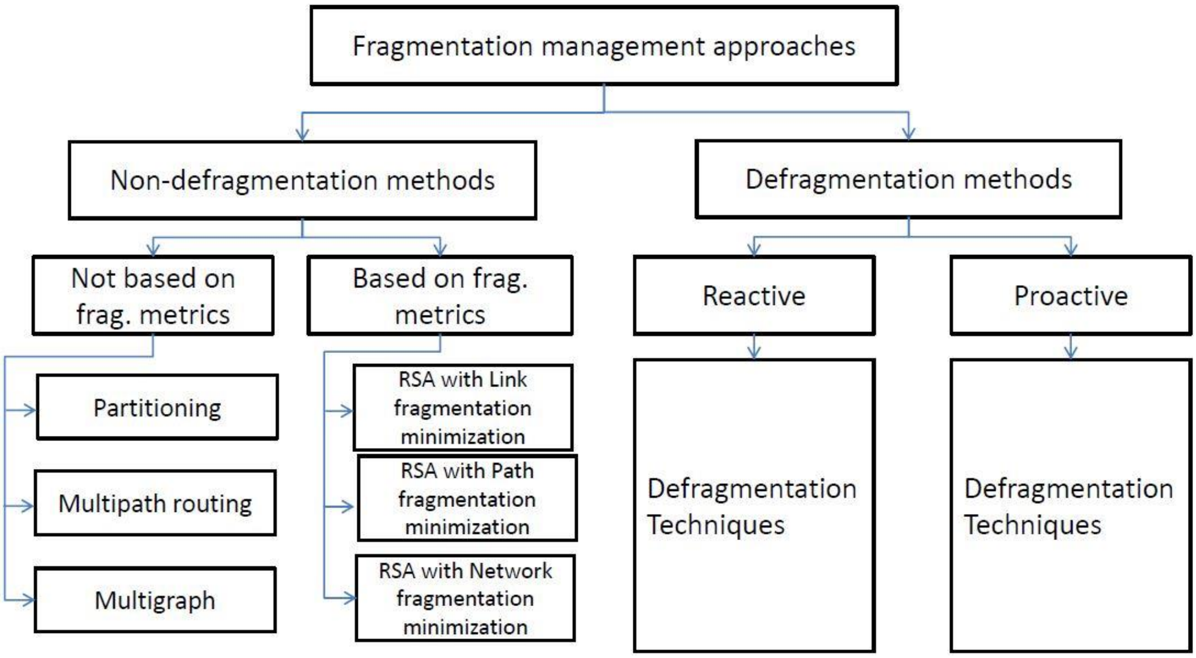



Figure 35 : Classification od defragmentation management approaches.

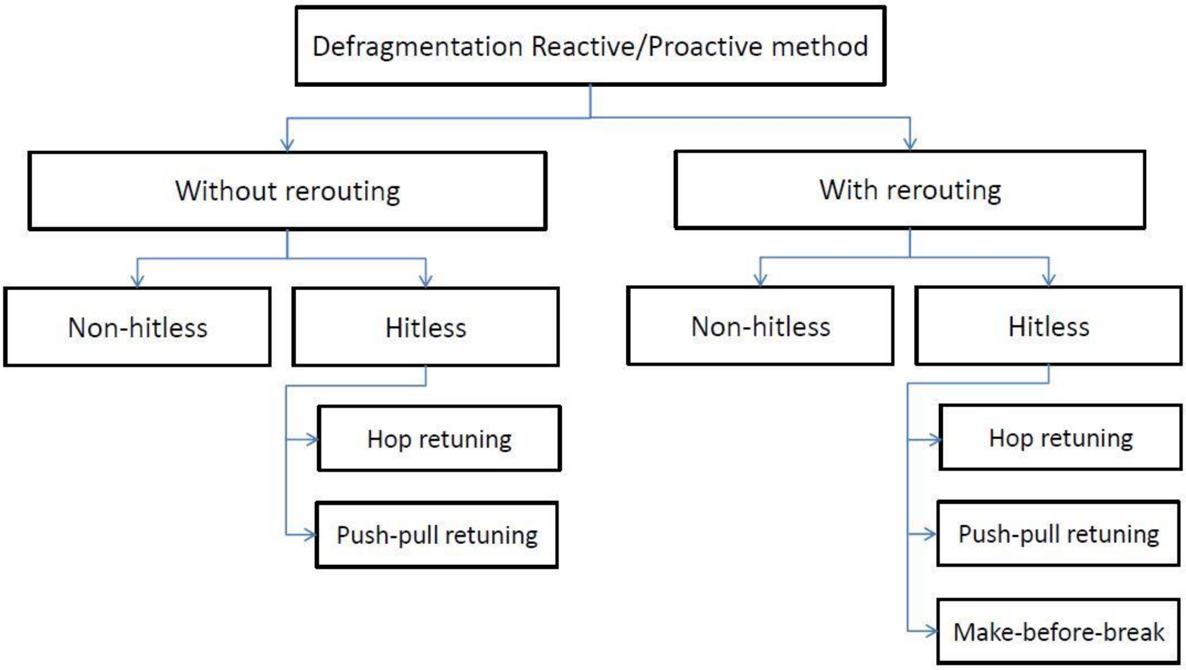



Figure 36 : Classification of defragmentation techniques for defragmentation methods (applied to both reactive and proactive methods). [20]

## *5.3 Non-defragmentation methods*

In non-defragmentation methods, the spectrum is managed in advance to avoid the spectrum fragmentation effect. These methods allocate the connection evaluating their impact on an index that measures the fragmentation level of the network. The non-defragmentation techniques conceived to bring lower capital expenditure (CAPEX) and operational expenditure (OPEX). However, methods belonging to this technique have lower performance in terms of admissible traffic volume than the one related to Defragmentation technique. In the Non- defragmentation techniques, the following strategies can be used to contain the spectrum fragmentation.

### 5.3.1 Non-defragmentation Techniques based on fragmentation metrics

Different allocation policies can be compared evaluating the connection demand blocking probability resulting from the adoption of each allocation policy in presence of dynamic traffic. The analysis is made on a single link where the incoming demands arrive to the system and their service time is characterized by an exponential probability distribution. Spectrum loss can be a metric to measure fragmentation; it occurs when a free slot cannot be utilized. Spectrum loss is demand sensitive because larger granularities are more likely to be blocked than smaller granularities. Therefore, it is not considered to estimate the level of fragmentation effect in EONs. The underlying assumption is that if the lower the blocking ratio, the lower fragmentation effect. However, the blocking ratio is not a complete measure of fragmentation as the blocking ratio is also impacted by several system parameters, such as lack of resources, quality of transmission, and holding time. Therefore, it is necessary to identify other comparison metrics to measure the blocking caused by spectrum fragmentation.

#### 5.3.1.1 RSA with link fragmentation minimization

The Shannon entropy metric can be applied to allocate minimum entropy in routing and spectrum allocation process. One of the recommended way to do so is the link-based minimum entropy, where the spectrum of each link along a path is considered individually. For each link in the path, the spectrum profile is necessary to find the starting locations with enough free spectrum slots, which supports the spectral width of transceiver. For each available position in the spectrum, the resulting difference ( $\Delta H_{frag}$) between the Shannon entropy of the spectrum with and without the new signal being placed there. After that, calculation process will go through. All other positions, which cannot provide enough free spectrum slots, are recorded as having an infinite difference. This process is repeated for the remaining links in the path and the sum of the entropy differences is calculated. The frequency slot that minimizes the cumulative entropy difference across all the links in the path is then selected.

| | f1 | f2 | f3 | f4 | f5 | f6 | f7 | f8 | f9 | f10 | f11 | f12 | f13 | f14 | f15 | f16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ΔHfrag(S1) | ∞ | ∞ | ∞ | -0.141 | -0.141 | ∞ | ∞ | -0.260 | ∞ | ∞ | -0.141 | -0.141 | ∞ | ∞ | ∞ | ∞ |
| ΔHfrag(S2) | ∞ | ∞ | -0.087 | 0.000 | -0.087 | ∞ | ∞ | -0.260 | ∞ | ∞ | -0.087 | 0.000 | -0.087 | ∞ | ∞ | ∞ |
| ΔHfrag(S3) | ∞ | ∞ | -0.087 | 0.000 | -0.087 | ∞ | ∞ | -0.260 | ∞ | ∞ | -0.087 | 0.000 | -0.087 | ∞ | ∞ | ∞ |
| ΔHfrag(S4) | ∞ | ∞ | ∞ | ∞ | -0.260 | ∞ | ∞ | 0.038 | 0.217 | 0.300 | 0.337 | 0.337 | 0.300 | 0.217 | 0.038 | ∞ |
| Sum(ΔHfrag) | ∞ | ∞ | ∞ | ∞ | -0.574 | ∞ | ∞ | -0.742 | ∞ | ∞ | 0.023 | 0.196 | ∞ | ∞ | ∞ | ∞ |

Figure 37 : Link Based Minimum Entropy Allocation. [23]

An example of calculating these metrics for a 4-link path with 16 frequency slots and a new demand requesting two slots is shown in Figure 37. The numbers given in the boxes show the resulting entropy difference ( $\Delta H_{frag}$) of placing the new demand starting at that location, and the line of numbers below the link-based example shows the overall differences for the path. Boxes containing '∞' indicate starting locations without enough free spectral slots to support this new two-slot demand. For the link-based technique, placing the new signal at ***f8*** has the lowest resulting entropy. Both Min entropy schemes should be applied over the k-shortest paths between the source and destination nodes to search for possible lower entropy routings and assignments.

### 5.3.1.2 RSA with path fragmentation minimization

Another way to go for fragmentation metrics evaluation is Shannon entropy-based routing and spectrum allocation which can be applied as path-based Minimum entropy. Here the spectrum profiles (represented by a bit sequence in which a **1** indicates a used spectrum slot and a **0** an unused spectrum slot) along all the links in the path are bitwise. By forming a single end-to-end profile, which is then searched (as described previously for a single link) to find the spectrum allocation that minimizes the entropy difference.

| ΔHfrag | f1 | f2 | f3 | f4 | f5 | f6 | f7 | f8 | f9 | f10 | f11 | f12 | f13 | f14 | f15 | f16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (S1+S2+S3+S4) | ∞ | ∞ | ∞ | ∞ | -0.311 | ∞ | ∞ | -0.311 | ∞ | ∞ | 0.141 | 0.141 | ∞ | ∞ | ∞ | ∞ |

Figure 38 : Path Based Minimum Entropy Allocation. [23]

Figure 38 is an example of path-based minimized entropy, where red indicates that a spectrum slot is already in use and green means that a spectrum slot is currently free. The numbers give the entropy difference (at path level) of adding a new two-slot demand starting at that slot, and which extends toward the right (higher *f* number). The infinity symbol indicates that for the two-slot demand request, those slots are unavailable either because they are already used or because the required neighboring slot to the right is already in use.

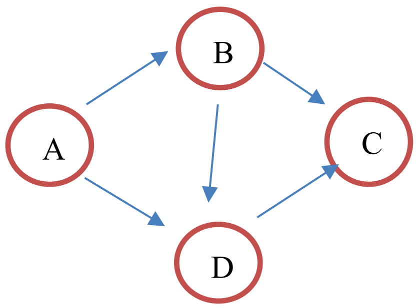
### 5.3.1.3 RSA with network fragmentation minimization

The fragmentation in a network can be measured also with the help of contiguous-aligned available slot ratio. We use the routes of source-destination pairs to represent the contiguous aligned available slot ratio in the network. The contiguous-aligned available slot ratio is defined by,

$$\boldsymbol{\Phi} = \sum_{\boldsymbol{d} \in \boldsymbol{D}} \sum_{\boldsymbol{k} \in \boldsymbol{kd}} w_{dk} . \Psi_{dk}$$

Where, $\Psi dk = \gamma dk / Z$ and $w_{dk}$ is a weight which is proportional to the traffic load of route $k \in kd$ of source-destination pair, where, $\sum_{\boldsymbol{d} \in \boldsymbol{D}} \sum_{\boldsymbol{k} \in \boldsymbol{kd}} w_{dk} . \Psi_{dk} = 1$

Z represents the number of spectrum slots in each link; we assume that all links have the same number of slots. D and $kd$ represent the set of all the source-destination pairs and the set of routes of source-destination $d \in D$, respectively. $\gamma_{dk}$ represents the maximum number of contiguous aligned available slots. The fragmentation is defined by $\boldsymbol{X} = \mathbf{1} - \boldsymbol{\phi}$.



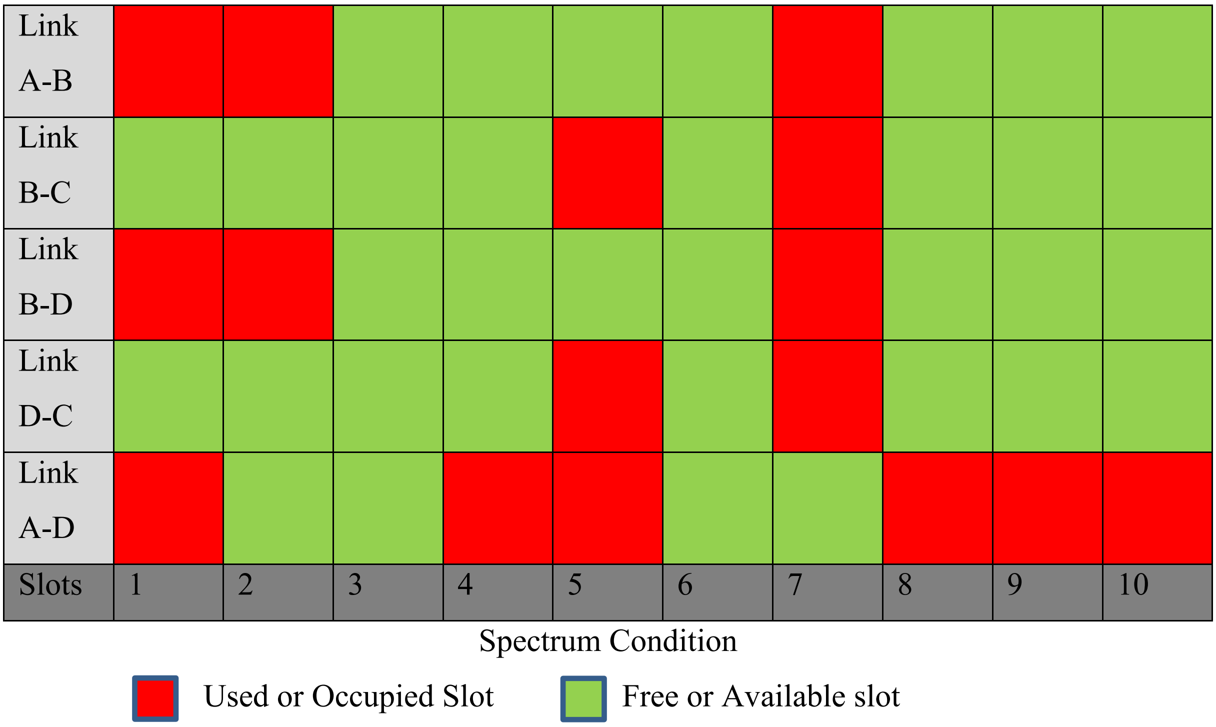



Figure 39 : Illustration of fragmentation in a network.

The fragmentation in a network is illustrated in Figure 39. We assume four-node network with five directed links. Each link consists of B=10 spectrum slots. We assume six source destinations pairs, which are AB (d = 1), AC (d = 2), AD (d = 3), BC (d = 4), BD (d = 5), and DC (d = 6). The routes of AB, AC, AD, BC, BD, and DC are A-B, A-B-C, A-B-D, B-C, B-D, and D-C, respectively. Here, B = 10 and |D| = |6|. For the sake of simplicity, we assume that each source-destination pair has one route. The traffic loads and the average number of requested slots for each source destination pair is the same over all the source-destination pairs. Therefore, with $|\,kd\,| = 1$ for all $d \in D$, $w_{d1} = 1/6$ is set. The contiguous-aligned available slot ratio and the fragmentation in the network are 0.466 and 0.533, respectively. [20]

### 5.3.2 Non-defragmentation techniques not based on fragmentation metrics

Three Non-defragmentation techniques not based on fragmentation metrics are briefly described in the following section.

### 5.3.2.1 Partitioning techniques

Two types of resource (i.e. spectrum on links) partitioning techniques can be applied in EON to mitigate the effect of spectrum fragmentation. The first one is the pseudo partitioning, and the second one is dedicated partitioning. The pseudo partitioning techniques are used to restore unsuccessful lightpath request by dividing them into two groups and allocating them to different ends of the spectrum. For example, a lightpath request that demands the bandwidth in a very high range is allocated resources from the lower end of the spectrum. On the other hand, request demanding smaller bandwidth are allocated on the higher end of the spectrum. The method avoids the direct accommodation (for instance, with first fit policy) of mixed types of lightpaths. Lightpath groups may be created based on higher bandwidth demand or lower bandwidth demand. Lightpath groups may also be created based on disjoint and non-disjoint routes of lightpaths.

Figure 40 shows an example of the spectrum allocation of lightpath request based on the pseudo partitioning method. In this case, the lightpath requests that demand a high bandwidth are allocated starting from the lower end of spectrum. On the other hand, the light path requests that demand a low bandwidth are allocated starting from the higher end of the spectrum.

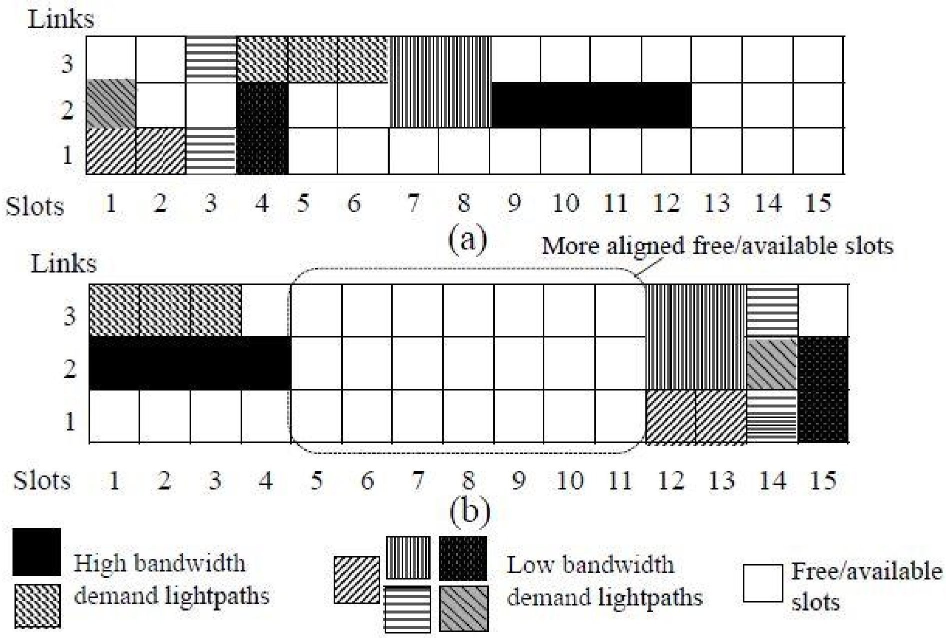



Figure 40 : Allocation of lightpath requests (a) without pseudo partitioning and (b) with pseudo partitioning. [20]

The dedicated partitioning techniques are the stricter version of the pseudo partitioning technique. In dedicated partitioning methods, the entire spectrum is divided into several partitions based on some criteria, and each partition is dedicated to a different lightpath group. In the following, the criteria to obtain the number of partitions is explained. The route and slot demand are assumed to be given for each lightpath group. The number of required partitions can be estimated using the graph coloring problem. The technique uses an auxiliary graph where the lightpath groups are considered as nodes and, if two lightpath groups share at least one common link, they are connected by an edge. A lightpath group is formed by a set of lightpaths whose routes are the same. The graph coloring problem assigns a color to each vertex while satisfying the constraint that the same color is not assigned to adjacent vertices; the objective is to minimize the number of colors. Each color corresponds to each partition unit. Minimizing the number of colors is equivalent to minimizing the number of partitions of the entire spectra.

### 5.3.2.2 Multipath routing techniques

The multipath routing technique deals with the contiguity constraint of the spectrum by means of a partial relaxation of the spectrum contiguity constraint. Multipath routing is also known as spectrum split routing. The concept of multi-path or spectrum split routing is presented in Figure 41. We consider a lightpath request L (Contiguous slots, Source, Destination). Let's assume that the lightpath requests arrive in the system in serial manner. We refer to the available slots are fragmented slots after the spectrum allocation of lightpath request $L_1$, $L_2$, $L_3$, …. $L_6$. In this context, if lightpath request $L_7$ arrives at node A for destination node C with demand of four consecutive slots. It is rejected as the required slots are unavailable. However, two lightpaths (i.e. A-B-C and A-D-C), each of which will utilize two consecutive slots, can be setup to service $L_7$. This type of routing, called multi-path routing or sometime spectrum split routing, is possible when the service profile allows, in case of fragmentation, the traffic splitting between multiple route.

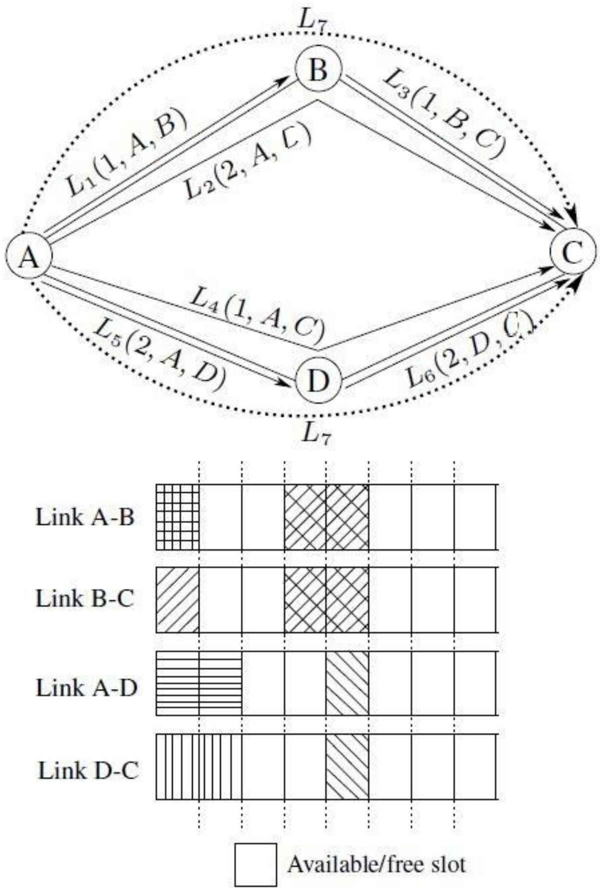



Figure 41 : Concept of multi-path or spectrum routing in EONs. [20]

### 5.3.2.3 Multigraph techniques

The Routing and Spectrum Assignment algorithms proposed in this section was designed to operate in networks with dynamic arrival of requests for the establishment of lightpaths. It is assumed that the RSA algorithm is implemented in ideal Path Computation Elements (PCE) and that information about the status of spectrum availability is stored in the PCEs databases. The proposed algorithm is, therefore, a first step towards the elaboration of algorithms that will include other aspects for coping with fragmentation.

It has been proved that the Routing and Spectrum Allocation problem is an NP-hard problem and heuristics are needed to solve the problem. The proposed algorithm models the spectrum availability in the network as labeled multigraph. A multigraph is a graph which is permitted to have multiple edges (also called "parallel edges"), that is, edges that have the same end vertices. In this auxiliary graph, vertices represent OXCs and edges the slots in the link connecting OXCs. All vertices are connected by N edges which is the number of slots in the spectrum of each network link. The label on an edge represent the slot availability. An ∞ value means that the slot is already allocated whereas the value 1 means that the slot is available for allocation. These values were defined to facilitate the employment of traditional shortest path algorithms.

The multigraph is transformed in N − b + 1 graphs where b is the bandwidth demand in slot of the requested channel. These graphs are generated by fixing an edge of the multigraph and considering the b consecutive edges to the fixed edge. This set of b edges of the multigraph are mapped onto a single edge of the generated graph. This technique's cost is caculated by applying a specific cost function that considers the b edges. [28]

## *5.4 Defragmentation methods*

The defragmentation methods can be arranged into two fundamental classes. The first one is reactive and the second one is proactive. Reactive defragmentation techniques are typically activated without waiting for the arrival of a new connection request, i.e. they take measures to leave enough resources available for future connections. Basically**,** the reactive algorithms are triggered when a connection request cannot be allocated due to the Spectrum Fragmentation, and the spectrum needs to be reconfigured to make enough room for the new connection request. In the reactive techniques, the defragmentation is triggered to allocate a connection request that would be blocked otherwise, usually by rerouting the established connections that will conflict with the selected route and slot-blocks for the new connection request. This necessary rerouting usually causes disruptions in the network.

On the opposite side, proactive defragmentation techniques are activated without sitting tight for another lightpath ask. In this case Defragmentation is triggered to allocate a connection request that would be blocked otherwise, usually by rerouting the established connections that will conflict with the selected route and slot-blocks for the new connection request. Both reactive and proactive are again grouped into two kinds. The rerouting techniques reallocate existing lightpaths to the various range openings by changing their paths to maintain a strategic distance from the negative impact. Then method without rerouting techniques don't enable existing lightpaths to change their courses, range reallocation might be permitted. In view of activity interruption, both with and without re-routing of existing lightpaths are ordered into the non-hitless and hitless defragmentation techniques. A periodic defragmentation scheme can be considered as proactive techniques. The proactive techniques are those where a defragmentation is invoked to consolidate the spectrum (minimize the total required spectral resources for the existing connections) and minimize the rejection of future connection request. It can be an algorithm executed periodically to reconfigure established connections, or a RSA algorithm that selects the route and spectral resources of a connection request, based on how fragmented that allocation will leave the spectrum (Fragmentation Aware).

### 5.4.1 Examples of non-hitless defragmentation algorithms

The defragmentation approaches that cause traffic disruption are referred as non-hitless defragmentation approaches. These approaches attempt to maximize the size of contiguous blocks of unassigned frequency resources with triggering traffic disturbance.

In the Figure 42, a simple representation of the considered non-hitless algorithms is shown.

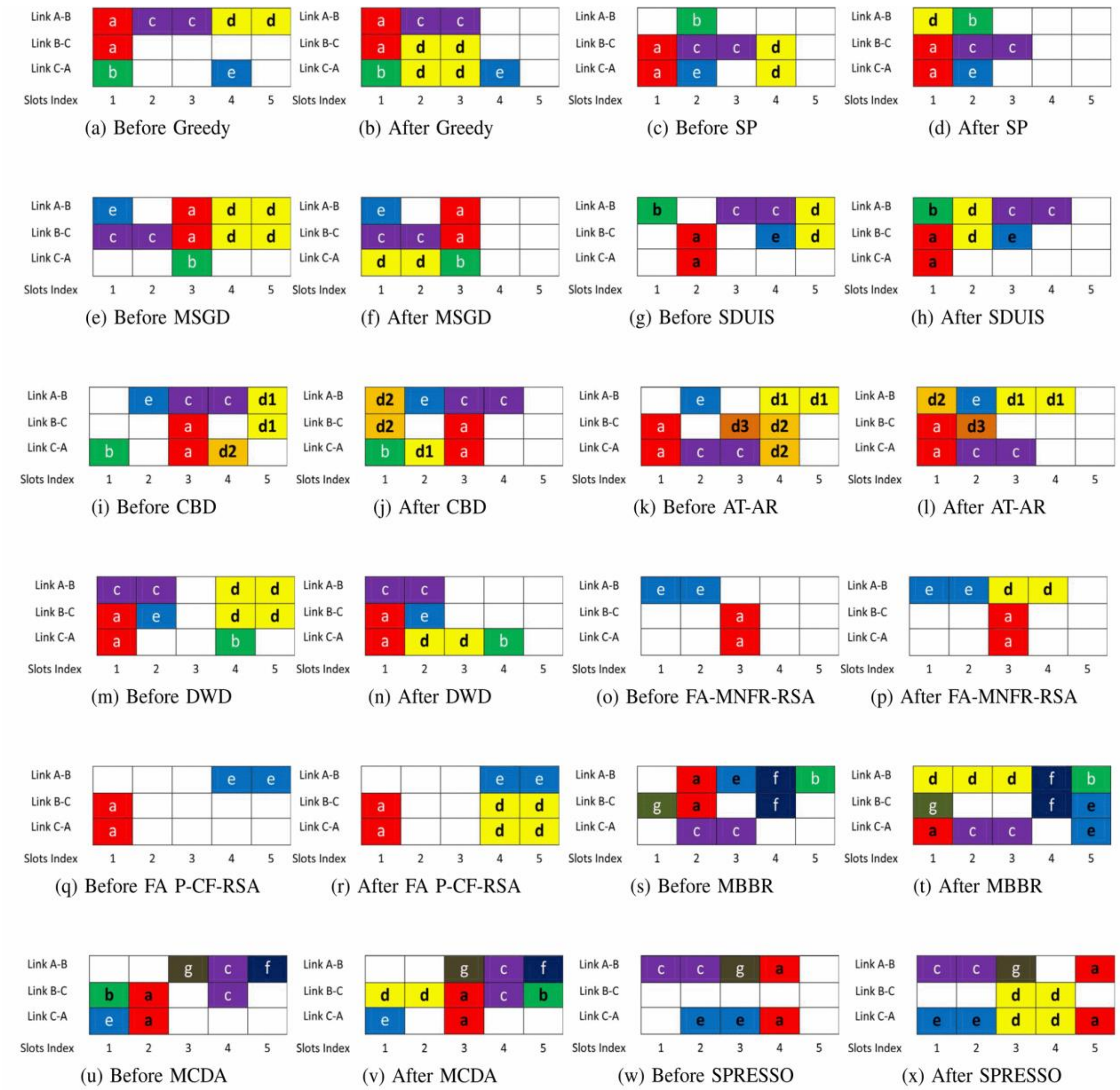



Figure 42 : Example of some non-hitless defragmentation algorithms taken from [21]

Firstly, we focused on two defragmentation algorithms, called Greedy, and Shortest Path (SP). The first one, selects k -shortest routes, and try to reroute every established connection in other ones with available slot-blocks with lower indexes, to leave a bigger number of contiguous slot-blocks on the higher indexes to accommodate future connections Figure 42 (a,b). The second one, makes the same steps, but selecting only the shortest available route Figure 42 (c,d).

A technique based on Spectrum Gain, that measures how much of the spectral resources a connection is utilizing, where every time a connection is terminated, and the resources on its route and FS are released, among all the connections that could improve the consolidation of the spectrum using these resources, the one with bigger Spectrum Gain is choosing to be rerouted. In Figure 42 (e) we can see that the connections and can be rerouted to the link between and ; finally, the connection  is selected in Figure 42 (f), because its rerouting has released more spectral resources, improving the consolidation of the spectrum.
A strategy using an auxiliary graph to minimize the Maximum slot-block Index (MSI), reassigning the established connections to slot-blocks with lower indexes, but in their own original route, starting with the connections with the longer routes Figure 42 (g,h). On the other hand, proactive strategy to minimize the disruptions on the network. Here, each time a certain number of connections is terminated, the defragmentation is invoked, selecting a portion of all the established connections to be rerouted with a best -effort strategy. This algorithm is represented in Figure 42 (i, j). Where a more exhaustive study is presented to answer the questions: What to Reconfigure? When to Reconfigure? How to Reconfigure? and How to migrate traffic? Here, it is being studied the best combination of RSA algorithms for reconfiguration, and the best way to migrate traffic.
Then, it is proposed an intelligent and adaptive selection of connections and the time of reconfiguration Figure 42 (k,1). A strategy of defragmentation, where the established connection with the longest holding time is constantly search for, to be rerouted to an optimal pair of route and slot-block. This strategy keeps the connections that will remain in the network for the longest time in the best possible state, so they would cause the least amount of conflicts with future connections request Figure 42 (m, n). Regarding the Fragmentation Aware RSA algorithms, a metric to measure the fragmentation of the network, called Network Fragmentation Ratio (NFR), where it tries to maintain the slot-blocks of bigger size available to accommodate future connections. Then it proposes an RSA algorithm based on NFR, where the route and the slot-blocks are selected according to the NFR of each candidate. In Figure 42

(o) a connection request with source  and destination in , that requires 2 (double) FS, can be assigned in A-C-B , but choosing this solution will get a bigger NFR comparing to  A-B , because it will use more slot-blocks, hence, increasing the NFR, this is why, the latter solution is selected Figure 42 (p).

A Fragmentation and Alignment Aware RSA algorithm, where, before the assignment of a route and slot-block, to a connection request, the following is considered: the number of slot-blocks that the connection will need, and the misalignment that this assignment will cause between the already available and aligned slot-blocks. An example of this algorithm is shown in Figure 42(q).

Suppose a connection request with source, and destination, that requires 2 FS. A candidate solution would be the assignation of to the link "A-B, but this will interfere with the existing alignment of the available slot-blocks in the three links, therefore, in Figure 42 (r), is allocated in, where it does not cause any misalignment. This work was extended to present a congestion avoidance strategy, that improves its performance in higher loads of traffic.

To minimize this disruption, A rerouting algorithm in a Make Before Break (MBBR) manner, where only if each one of all the connections in conflict with the new connection request find an alternative route, then these are rerouted without releasing their original resources yet. Until all the connections are established in their new route, and the resources of the old ones are released, then the new connection request can be allocated. The Figure 42 (s, t) shows how the connections and had to be rerouted for to be allocated.

A strategy where a pair of route and slot-block, with the least number of established connections in conflict with a new connection request is searched. When this pair is found, the connections in conflict are reassigned on different slot-blocks, but in the same route, to give room for the new connection to be allocated Figure 42 (u, v). Lastly, a strategy where if enough FS are available in one of the shortest routes, the defragmentation is triggered, to find a set of already established connections, and then reassigned them on contiguous available FS, to make enough room for the connection to be allocated Figure 42 (w,x).

### 5.4.2 Methods (rerouting vs non-rerouting and hitless vs non-hitless)

The reconfiguration schemes in defragmentation methods can be split into two types. One is non-rerouting and the other is rerouting.

In non-rerouting scheme, when the connections are reconfigured, the portion of the occupied spectrum moves to a new one, but not its original route. In rerouting, both the slot blocks index and he original route can be modified.

The defragmentation techniques that can't avoid the service interruption during the defragmentation are defined as non-hitless defragmentation techniques. These methodologies attempt to amplify the span of adjoining squares of unassigned assets with activating movement of unsettling issues. As these methodologies dependably aim at activity interruption, they are not preferred in EONs. To beat this issue, hitless defragmentation techniques are considered for EONs.

The defragmentation methods that do not cause any traffic disruption are referred as hitless defragmentation techniques. These techniques attempt to maximize the size of contiguous blocks of unassigned frequency resources without triggering any traffic disturbance. Figure 43 shows an example of hitless defragmentation and its different conditions. Initially, lightpaths 1 to 4 are active in Figure 43. Then lightpath 2 is terminated in Figure 43 (b), and we apply hitless defragmentation to retune lightpaths 3 and 4 in Figure 43(c). Finally, lightpath 5 is added to the network in Figure 43. In this example, lightpaths are retuned based on proper reconfiguration of allocated spectrum resources.

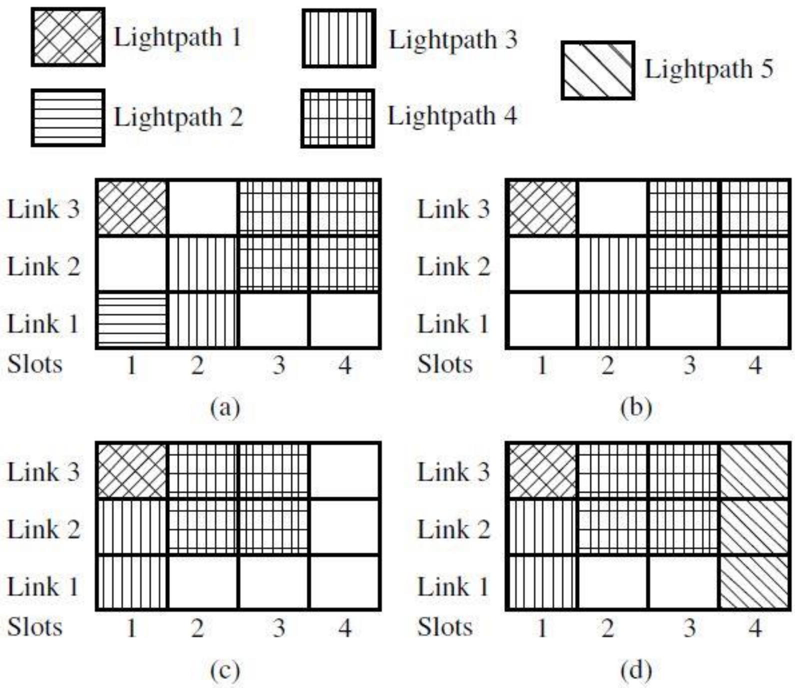



Figure 43 : Example of different condition of hitless defragmentation (a) initial state, (b) lightpath 2 terminated, (c) defragmentation using hitless, and (d) lightpath 5 added in the network.

To achieve hitless defragmentation, a flexible optical node architecture is essential. Figure 44 shows the node architecture that offers hitless defragmentation. It uses a pool of flexible transceivers, instead of several types of dedicated transponders to satisfy the client demand. If dedicated transponders are used, flexibility is insufficient, and hence hitless defragmentation cannot be performed. This is because the synchronization among all involved devices cannot be performed in a coordinated manner under distributed control environment or a centralized network controller. In this node architecture for hitless defragmentation, client-side devices no longer include the transceivers; all transceivers are placed in a flexible transceiver pool. The client side generates a signal, which is mapped to transport frames, and the modulation format is decided. A bandwidth variable cross-connect switch (BV-WXC), which is placed between the client side and the flexible transceivers pool, enables the sharing of transceivers from the flexible pool. Using this architecture, the client selects a suitably configured flexible transceiver.

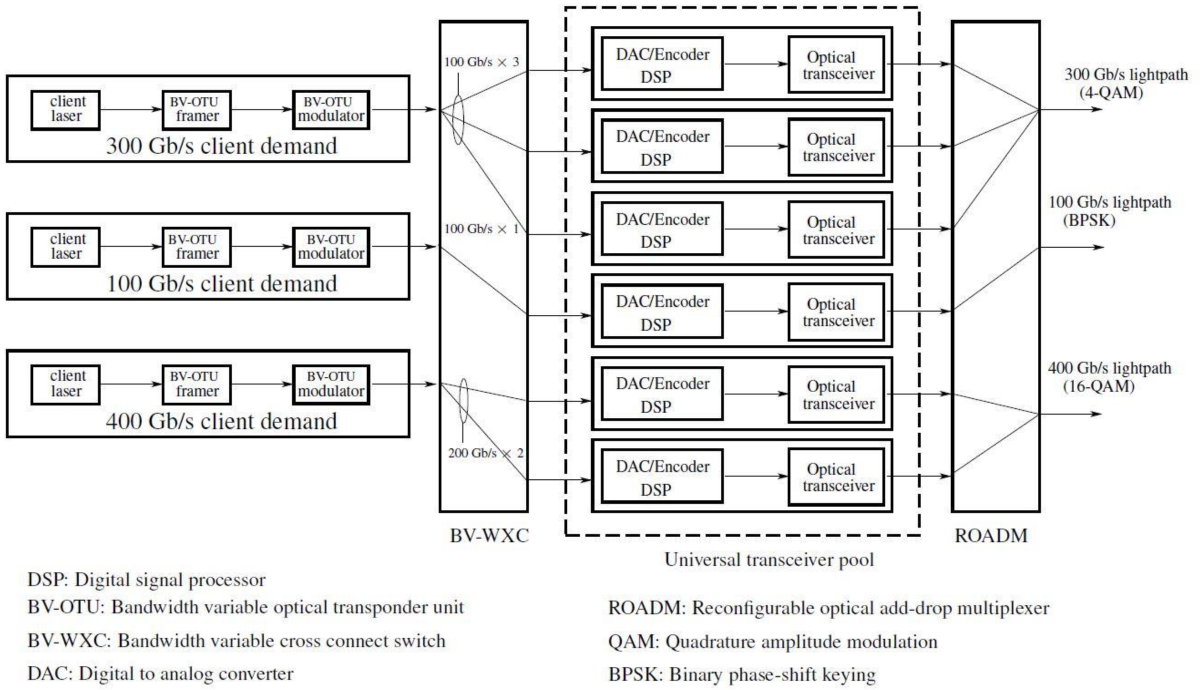



Figure 44 : Node architecture of hitless defragmentation. [20]

The Table 11 presents a summary of non-hitless defragmentation algorithm considering both rerouting and non-rerouting.

| | Proactive | Reactive |
|---|---|---|
| Rerouting | **Greedy** | **MBBR** (Make before Break) |
| | **SP** (shortest Path) | |
| | **MSGD** (Maximum spectrum gain defragmentation) | |
| | **CBD** (Comprehensive bandwidth defragmentation) | |
| | **AT-AR** (Adaptive timing and Adaptive ratio) | |
| | **DWD** (Double window Defragmentation) | |
| NON- REROUTING | **SDUIS** (Spectrum defragmentation using independent sets) | **MCDA** (Multi criteria Decision Analysis)<br>SPRESSO |
| | **FA MNFR** (Fragmentation aware- Minimum network fragmentation ratio) | |
| | **FA PCF** (Fragmentation aware- preselected compromised fragmentation) | |
| | **FA RSA** (Fragmentation Aware- Routing and spectrum allocation) | |
| | **FA CA RSA** (Fragmentation Aware- Congestion avoidance RSA) | |

Table 11 : Summary of Non-Hitless Defragmentation Algorithm. [21]

### 5.4.3 Techniques in defragmentation methods

There are three main defragmentation techniques: hop-retuning, push pull retuning and make before break. The first two can be applied in association with rerouting or with non-rerouting schemes, while the third requires necessarily the rerouting scheme. These defragmentation techniques can be applied in both hitless and non-hitless methods and are described in detail here below.

#### 5.4.3.1 Hop retuning techniques

The technology for hop retuning was introduced by R. Proietti et al. A simple three-node network scenario for demonstration of hop retuning as shown in Figure 45 (a). In Figure 45(b) shows the spectrum reallocation of the different lightpaths, namely lightpath 1, lightpath 2, and lightpath 3, on links A-B and B-C before and after the defragmentation processes. We assume that each lightpath needs one slot and the central frequencies of slots 1, 2 and 3 are f1, f2, and f3, respectively. Lightpath request 4 arrives for lightpath establishment from node A to node C. On link A-B, slot 1 is available but the same spectrum slot is not available on link B-C. An efficient usage of the spectrum resource is to move lightpath 1 from slot 1 to slot 3 on link B-C. In this way, spectrum resource can be available on link B-C to establish new lightpath 4. Note that the spectrum reallocation can also be performed, as a special case when a lightpath occupies few contiguous spectrums slot. This retuning process does not disrupt any existing lightpath and it can be implemented with the help of following concept.

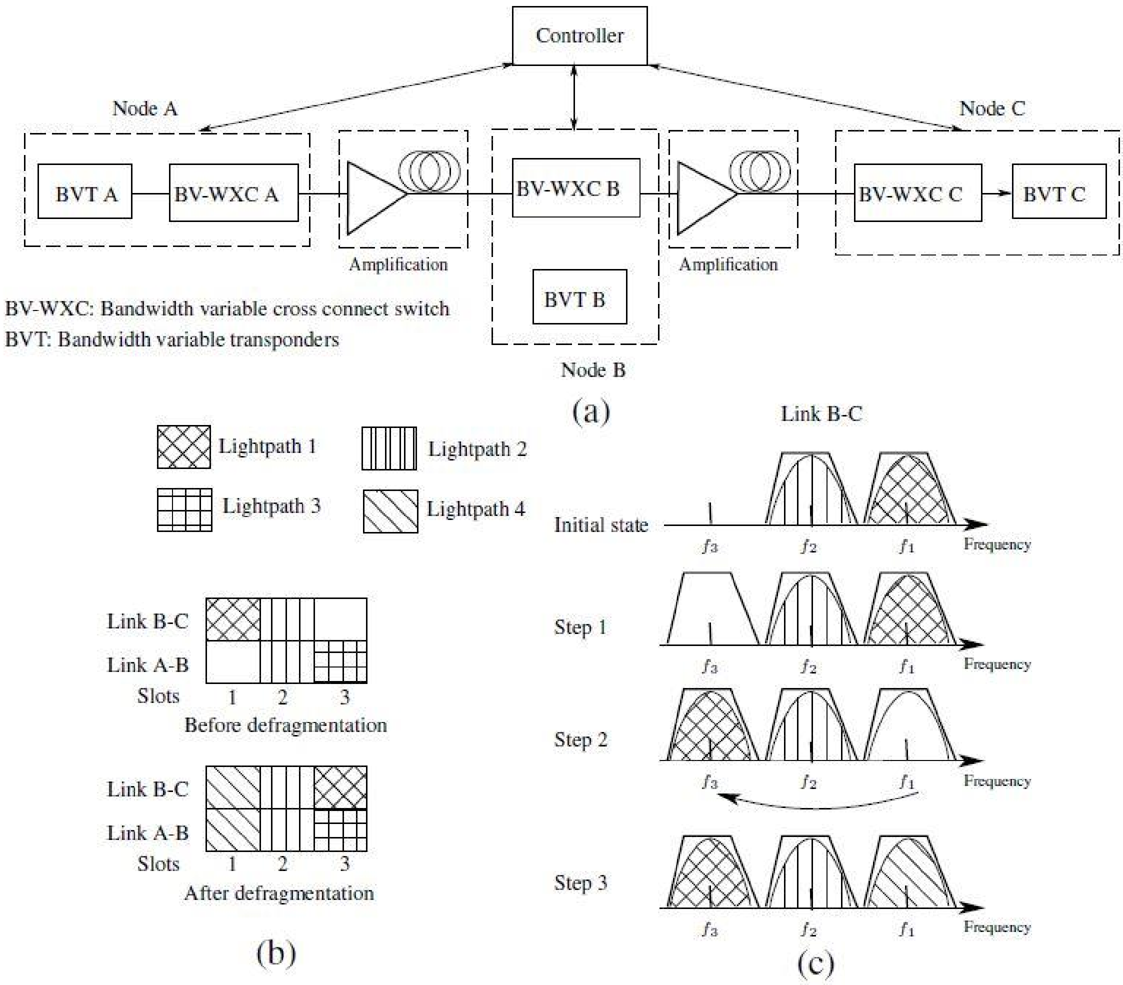



Figure 45 : Concept of Hop Retuning (a) three node network scenario, (b) spectrum reallocation before and after defragmentation, (c) Defragmentation steps with BV-WXC reconfiguration to accommodate new lightpath. [20]

### 5.4.3.2 Push-Pull retuning techniques

The push and pull technology can cover the entire spectrum grid range. It is executed gradually step-by-step and spectrum jumps are not allowed. It is executed by synchronizing devices under a centralized or distributed control environment. Execution of this technique does not involve re-routing of lightpaths, so traffic disruption does not occur. The time taken for retuning in the push pull techniques is determined by the retuning step width, such as 2.5 GHz, and sweep rate, such as 1, 10, 100, or 1000 ms /step. As an example, in an EON with 12.5 GHz granularity, each step requires five ms per slot, and sweep rate of one ms/step. Similarly, 0.5 sec is required for sweep rates of 100 ms/step [20]. Hitless defragmentation is achieved by Push-Pull retuning, as shown in Figure 46. To avoid traffic disruption, existing lightpaths are continuously swept. The sweep time is one of the significant system parameters for handling dynamic traffic. During a continuous sweep, the compensation of frequency offset between the tunable transmitter laser and the oscillator laser of the receiver is compulsory in the transceiver pool. The total defragmentation time mainly depends on (i) propagation delay between transmitter and receiver, (ii) signaling method for wavelength sweep, and (iii) sweep speed of tunable lasers.

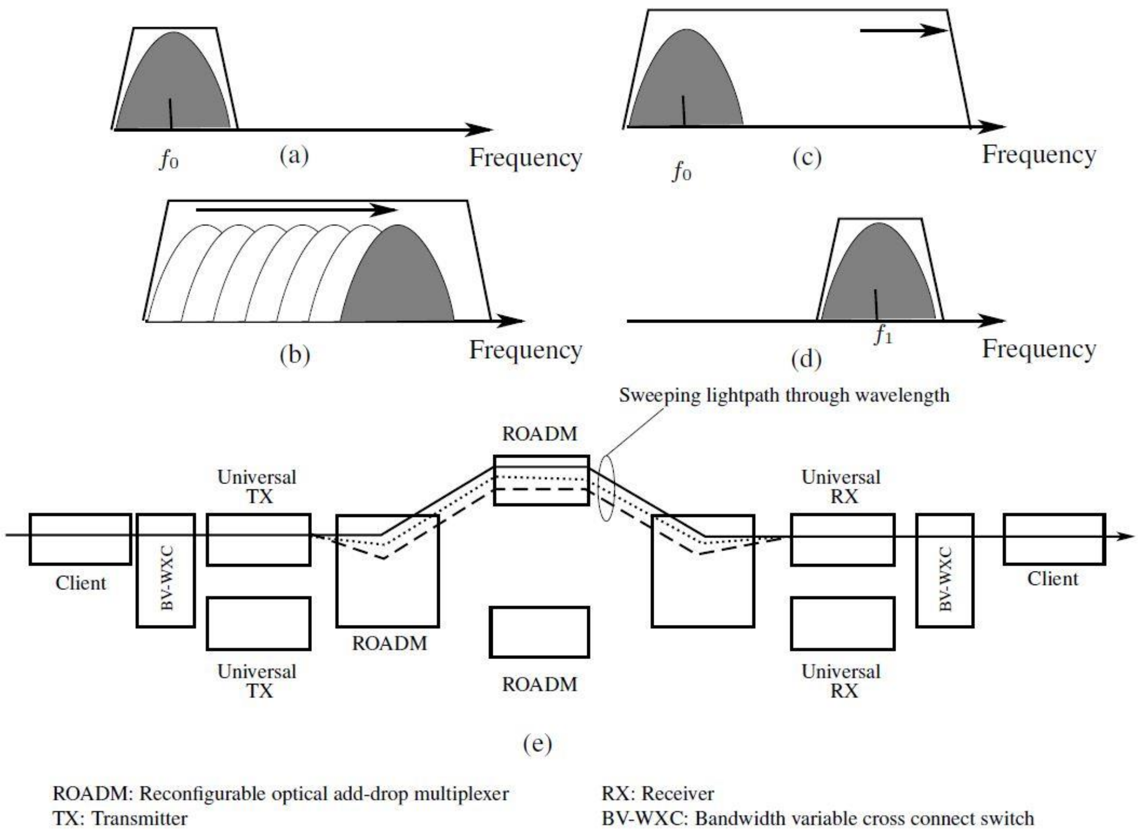


Figure 46 : Illustration of Push-Pull retuning (a) initial condition (b) adjusting for sweeping of established lightpath (c) continues seeping of established lightpath, (d) final condition after sweeping, and (e) sweeping lightpath on the same route through wavelength. [20]

### 5.4.3.3 Make-before-break techniques

The make-before-break technique can also be used to achieve hitless defragmentation. In the make-before-break technique, an additional lightpath between the same source-destination pair is setup while the original lightpath remains active. The routes of original and additional lightpaths should be link disjoint, and the traffic is switched between the two lightpaths. Finally, the original lightpath is torn down, and the traffic carried through the newly-established lightpath. The concept of the make-before-break technique is explained in Figure 47. The main limitation of the make-before-break technique is that it needs the additional resources and transponders that allow hitless defragmentation. A further issue with the make-before-break technique is the additional operations required in the optical layer. The establishment and release of lightpaths depend on the number of associated fiber links, including optical amplifiers. This force composite optical power equalization, which may affect the stability of other active lightpaths.

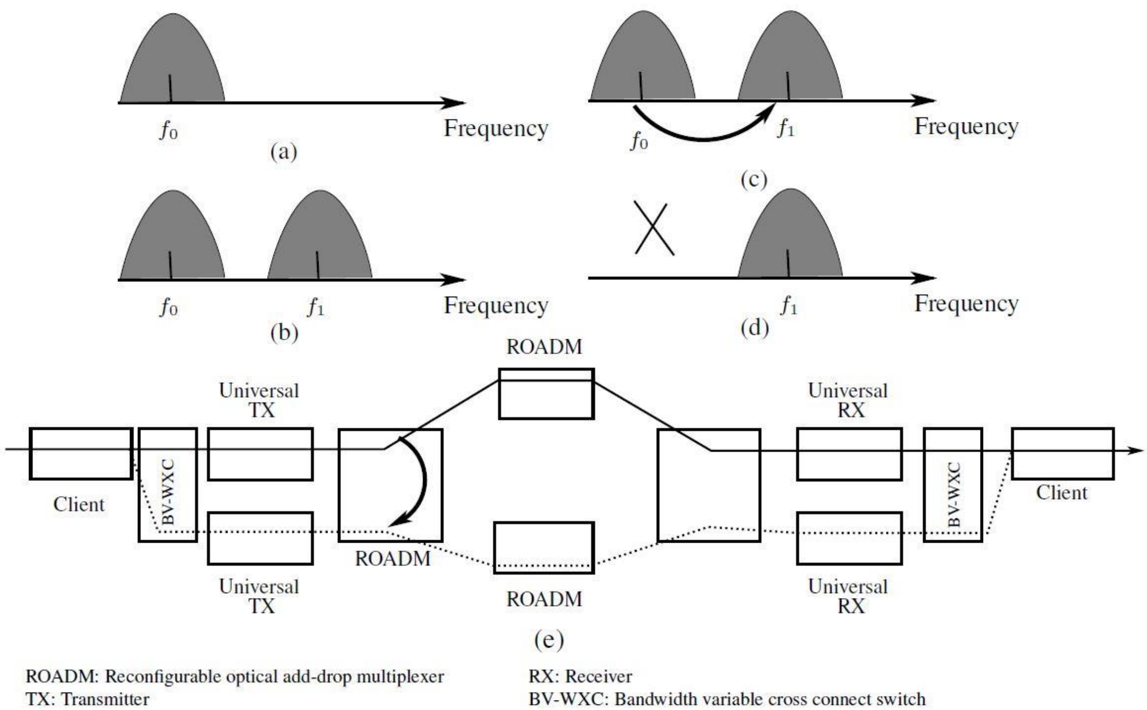


Figure 47 : Illustration of make before break technique (a) initial condition, (b) additional lightpath establishment, (c) traffic switching between original lightpath and additional lightpath, (d) termination of original lightpath, and (e) switching lightpath from original path to new path. [20]

## 5.5 Evaluation and comparison of Non-defragmentation techniques

This subsection compares the results of different non-defragmentation techniques, which are partitioning techniques, and multipath routing techniques. These techniques are already described in section 5.3.2.

Figure 48 plots the blocking probability versus traffic volume obtained by using different non-defragmentation techniques. For comparison, this section incorporates the results of RSA technique without considering any precaution to avoid fragmentation before the establishment of a lightpath. In RSA, considering fixed shortest path routing and first fit policy for spectrum allocation. Observing that the blocking probability is greatest with the RSA technique. Furthermore, noticing that the multipath routing technique yields lower blocking probability than the RSA technique. This is because the multipath routing technique splits bandwidth requests into various parts and it transfers these parts along one or more lightpaths by utilizing sliceable bandwidth variable transponders. Finally, it can be observed that the partitioning technique provides the lowest blocking probability among all non-defragmentation techniques considered.

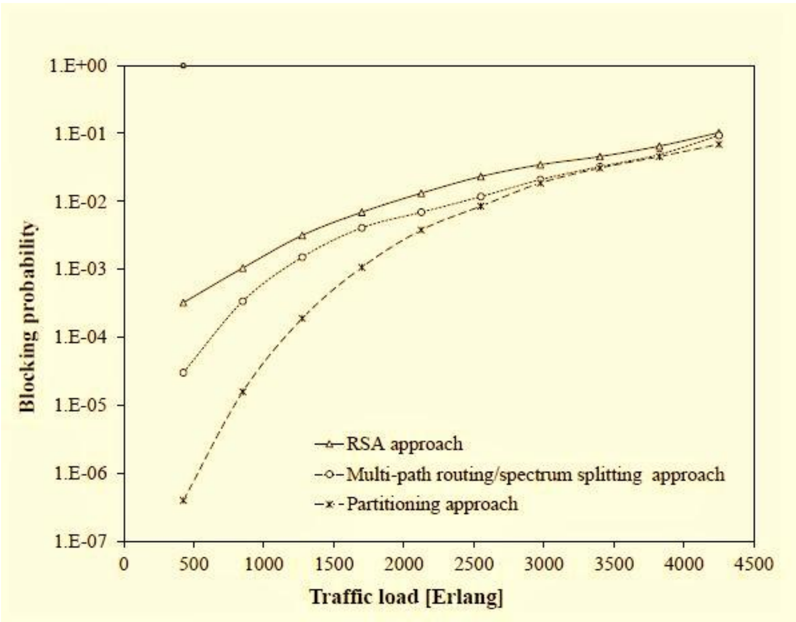



Figure 48 : Comparison of blocking probabilities using different non-defragmentation techniques. [20]

The first-last fit spectrum allocation policy is suitable for the partitioning technique. Therefore, in the partitioning technique, using the first-last fit spectrum allocation policy with the constraint where lightpaths assigned to identical partitions must be link disjoint. To satisfy the link disjoint constraint, dividing the entire spectrum into 14 partitions by solving a graph coloring problem. All odd and even partitions are allocated using first fit and last fit policies, respectively. Comparison says that the partitioning technique offers more aligned available slots and the first-last fit spectrum allocation policy provides more contiguous available slots. As a result, the partitioning technique offers higher contiguous-aligned available slot ratios than the other non-defragmentation techniques considered, which is captured in Figure 49.

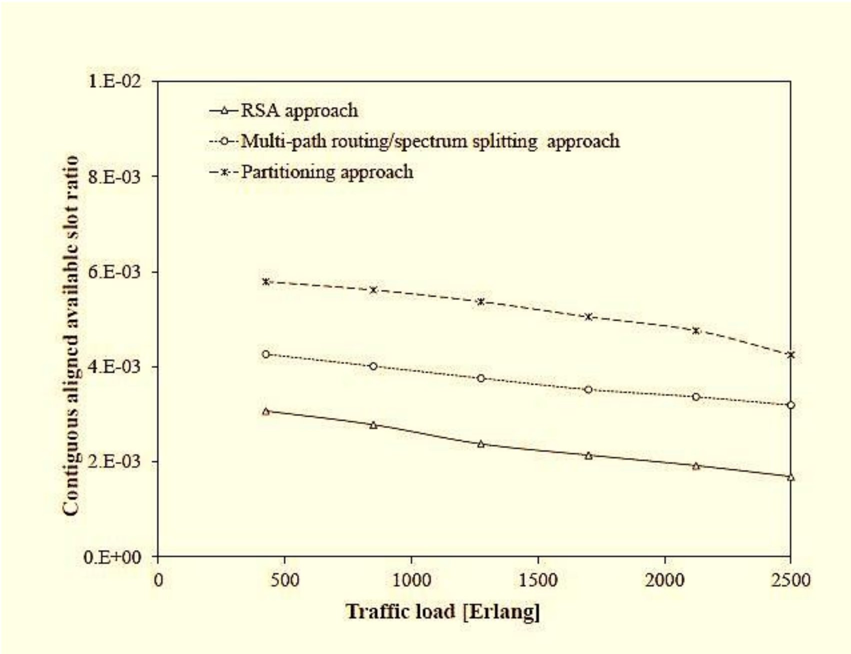



Figure 49 : Comparison of contiguous-aligned available slot ratios using different non-defragmentation techniques. [20]

## 5.6 Evaluation and comparison of Defragmentation techniques

Table 12 compares non-hitless defragmentation and hitless defragmentation techniques. The main advantages of non-hitless defragmentation techniques are that they can be deployed without additional equipment. However, they often cause traffic disruption. They are inferior to hitless defragmentation techniques in terms of spectrum defragmentation. As a result, when sensitive data transmission is required without traffic disruption, hitless defragmentation techniques are preferred. Among different hitless defragmentation techniques, hop retuning provides the best performance in terms of suppressing the fragmentation effect. However, hop retuning is not implemented in finely granular systems, such as 2.5 GHz frequency spacing, due to the current lack of filtering equipment, and equipment costs are high. The make-before-break technique suppresses fragmentation by sacrificing additional resources and transponders, which support retuning in the hitless manner. Push-Pull retuning can be used for all levels of spectrum granularity including finely-granular systems, and significantly suppresses bandwidth fragmentation. The defragmentation channel per step indicates the number of channels considered for defragmentation process in each step. The defragmentation channels per step for make-before-break, push-pull retuning and hop retuning are single, single and multiple, respectively.

| Evaluation Parameters | **Non-hitless Defragmentation** | | **Hitless Defragmentation** | | |
|---|---|---|---|---|---|
| | Rerouting | Without re-routing | Hop retuning | Push-Pull retuning | Make before break |
| **Extra equipment** | No | No | Yes | Yes | Yes |
| **Interrupt traffic** | Yes | No | No | No | No |
| **Defragmentation channel per step** | N/A | N/A | Multiple Channel | Single Channel | Single Channel |
| **Defragmentation speed** | N/A | N/A | Rapid (<1µs) | Slow | Fast |
| **Cost** | Low | Low | High | Moderate | Maximum |
| **Complexity** | Higher than without rerouting | Lowest | Highest | Higher than non-hitless | Higher than push pull |
| **Defragmentation Spectral Area** | N/A | N/A | Any | Limitation | Any |

Table 12 : Comparison of different defragmentation techniques. [20]

Figure 50 plots the blocking probability versus traffic volume obtained by using different hitless defragmentation techniques. We observe that the push-pull retuning technique yields higher blocking probability than the other hitless defragmentation techniques as it suffers a bottleneck due to end-of-line situations. An end-of-line situation occurs when a lightpath cannot be returned to fill in a gap left by an expired lightpath due to the interference of another lightpath which prevents it from being moved further. The make-before break technique offers lower blocking probability than the push-pull retuning technique. In case of the make-before-break technique, lightpath requests are not blocked due to end-of line situations; the make-before-break technique establishes an additional lightpath between the same source-destination pair along with the original lightpath, and the traffic is continued through the newly-established lightpath. Note that the original lightpath is torn down after establishing the additional lightpath. As a result, the call blocking probability is suppressed. The hop retuning technique achieves the lowest minimum blocking probability among all defragmentation techniques considered. This is because it retunes lightpaths to any available spectrum slot regardless of whether it is continuous or not; the bottleneck due to end-of-line situations can be overcome by using the hop retuning technique. Additionally, the hop retuning technique does not require any additional lightpath for bandwidth defragmentation, unlike the make-before-break technique.

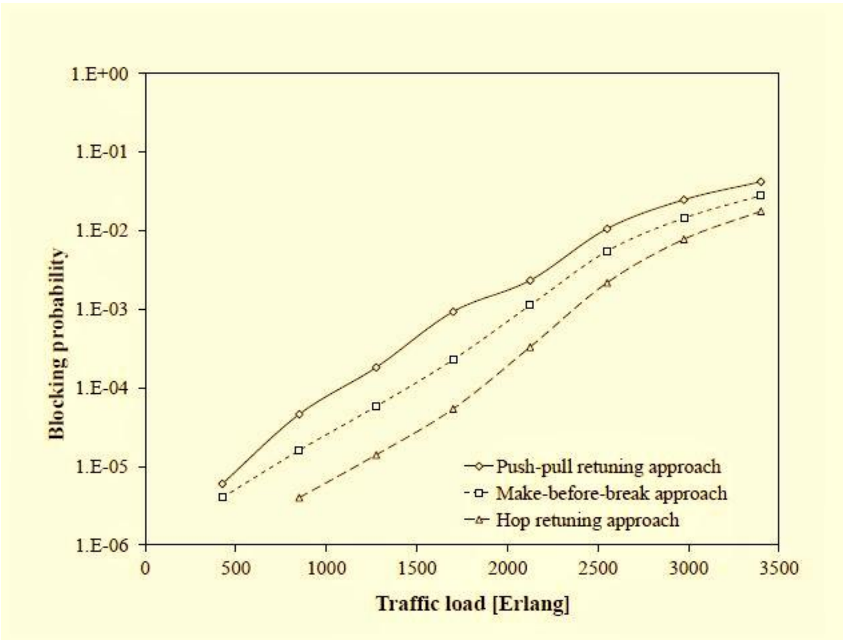



Figure 50 : Comparison of blocking probabilities using different hitless defragmentation techniques [20]

# 6 Conclusions

In the conclusion of my thesis, I can say that spectrum defragmentation is a significant topic that needs to take further research because of its variability. The need of spectrum defragmentation in EON networks is highly recommended, as this makes the network reliable. Different kind of defragmentation methods gives a technique on how to solve the problems of fragmentation effect. It improves the reliability of the network and overall performance.

The elastic optical networks are still in a research state and its development still presents some issues that need to be solved. However, EON does provide new exciting features that could lead to an improvement over the traditional spectrum management of optical networks. As services offered increment and the demands of the user increase over time, it is logical the change of WDM system of spectrum allocation to EON architecture because of its flexibility and scalability necessary for the more demanding growth of network traffic. By using the flexible use of bandwidth and appropriate spectrum allocation of the varied sizes of connections, this technology is the best appropriate for the future necessities of the optical networks.

Bandwidth fragmentation is a serious issue in EONs and ignoring it can increase the call blocking in the network. To suppress bandwidth fragmentation, researchers have been focusing on architectures of EONs and spectrum allocation mechanisms. The first is powered by transponders capable of generating multiple modulation formats at variable symbol rates so that transmission can cope with dynamic traffic conditions and suppress bandwidth fragmentation. This change has been mad possible by significant advances in the field of wavelength selective switch (WSS), which are now capable of switching spectrum under 2.5 GHz frequency spacing. This made the realization of flexible ROADM architectures for EONs. Basically, spectrum defragmentation is focusing on suppressing bandwidth fragmentation, adjustment of latency, blocking probability and resource occupation rate.

The study of several demonstrations on bandwidth defragmentation approaches suggest that they can be implemented in practical networks in order to accommodate more admissible traffic and fulfill the clients demand. The performance of hitless defragmentation approaches in terms of spectrum defragmentation is better than that of non-defragmentation approaches. It can also be realized that capital expenditure and operational expenditure of hitless defragmentation approaches are larger compared to non-defragmentation approaches, hop retuning provide the best performance in terms of suppressing the fragmentation effect.

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