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ROUTING AND SPECTRUM ALLOCATION ALGORITHMS FOR FLEXIBLE GRID METRO NETWORKS

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Because the only people for me are the mad ones, the ones who are mad to live, made to talk, mad to be saved, desirous of everything at the same time, the ones who never yawn or say a commonplace thing, but burn, burn, burn like fabulous yellow roman candles exploding like spiders across the stars and in the middle you see the blue centerlight pop and everybody goes "Awww!"

"*On the Road*"

Jack Kerouac

Preface

The thesis is submitted as the final work for the degree of Master of Science in Telecommunication Engineering, that has been taken by the author at the university Politecnico di Milano. The specialization Telecommunication Networks has been chosen as part of the double-degree exchange program TIME (Top Industrial Managers of Europe). The report is based on the work conducted by the author in the period May 2011- October 2012 on a thesis assignment by the Department of Electronics and Information (DEI), under the supervision of the full professor Achille Pattavina and the assistant professor Massimo Tornatore.

I wish to thank Massimo for the valuable feedbacks and the constant and helpful support. I will treasure the opportunity I received by working on such an interesting project. I also take the opportunity to thanks Francesco Musumeci, PhD student at DEI, for his tremendous support on the final drafting and commenting of this work.

A sincere and heartfelt thanks to all the people who shared with me this study experience.

Sommario

Nell'ultimo decennio, il volume di traffico Internet generato è cresciuto in maniera esponenziale, e non si prevede un rallentamento di tale crescita nel breve periodo. Il prosperare di applicazioni dall'alta richiesta di banda, l'introduzione del moabile broadband con voluminosi scambi di dati e l'evoluzione di servizi integrati voce-video-dati, continuano a porre notevole pressione sulle reti di telecomunicazione. Migliorìe importanti sono state portante avanti nei segmenti di backbone e di accesso di tali reti. Tuttavia, il segmento metropolitano non ha visto sfozi verso il miglioramento di egual intensità, creando un effetto di collo di bottiglia comunemente chiamato "metro gap". Gli effetti negativi del "metro gap" rischiano di rendere vani gli sforzi sugli altri segmenti. Nelle reti metropolitane, un utilizzo efficiente delle risorse già in campo è un fattore chiave.

Nelle reti metro, lo standard trasmissivo dominante è stato SONET/SDH, il quale è molto efficace per reti metro ad anello nella condizione di traffico prevalentement voce. Con il passaggio da traffico prevalentemente voce a traffico prevalentemente dati, come nello scenario attuale, si è verificato un disaccoppiamento tra traffico e ricavi. SONET è pertanto una soluzione non più ottimale. Resilient Packet Ring prima, e Metro Ethernet poi, si sono proposti ai network operator con interessanti vantaggi; quest'ultimo sembra particolarmente visto di buon occhio.

L'introduzione della ITU-T Recommendation G.694.1 permettere di dare una brusca sterzata dai precedenti sistemi trasmissivi, i quali sono basati su una divisione dello spettro ottico in lunghezze d'onda distanziate 50 GHz. Con Rec. G.694.1 viene superata la traizionale visione dello spettro ottico come un insieme di lambda, ciascuna indipendente dall'altra; in Rec. G.694.1 la banda a disposizione è vista come un continuum dove le risorse ottiche necessarie possono essere allocate in maniera flessibile. È introdotto il concetto di flexible grid.

Nella tesi è sviluppata una analisi dei vantaggi dovuti alla flexible grid. Viene proposto un algoritmo di Routing and Sepctrum Allocation in reti metro, tenendo in considerazione diverse strategie di allocazione e rilascio delle risorse e ottimizzando

diverse funzioni di costo. Inoltre, vengono esplorati i vantaggi dovuti all'utilizzo del Multiple Modulation Formats invece che un unico formato di modulazione prefissato.

L'analisi mette in risalto che, grazie ad una efficiente allocazione del traffico, la tecnologia con flexible grid introduce importanti benefici. È mostrato inoltre come le diverse strategie influenzino l'utilizzo delle risorse di rete. Infine, ulteriori vantaggi dovuti alla tecnologia MMF sono dimostrati.

Abstract

In the last decade, Internet traffic has experienced an exponential growth which is not expected to slow down anytime soon. Flourishing of bandwidth-hungry applications, together with the introduction of data-centric mobile broadband and the evolution of triple-play services, continue to put a high pressure on telecommunication networks. Significant improvements had been introduced in the backbone and in the access segment of telecommunication networks. Nevertheless, not equally significant efforts had been brought into the metro area, creating a bottleneck effect which is commonly referred to as “metro gap”. The negative consequences of the “metro gap” risk to vanish the efforts on the other segments. In metropolitan areas efficient exploitation of already deployed resources is a key factor.

In metro networks, the leading transmission technology has been the SONET/SDH standard, very effective in the metro rings for voice-centric traffic. With the decoupling of revenues from traffic into data-centric present scenario, SONET is not any longer a cost-effective solution. Resilient Packet Ring first and Metro Ethernet after have presented interesting benefits to the network operators; the latter is presently seen as the most interesting solution.

The introduction of ITU-T Recommendation G.694.1 allows to steer away from legacy transmission systems, which are based on the DWDM 50-GHz wide spacing of the optical spectrum. The traditional vision of the available optical spectrum as a set of wavelengths, each independent from the other, is overcome with Rec. G.694.1, in which the available bandwidth is seen as a continuum where the required resources can be allocated in a flexible fashion. Thus, the flexible grid concept is introduced.

An analysis of the benefits brought by the flexible grid is carried out in this thesis. An algorithm for the Routing and Spectrum Allocation (RSA) in metro networks is proposed, considering different strategies for the resource allocation and release and different cost functions to be optimized. Moreover, the advantages of exploiting Multiple Modulation Formats (MMF) rather than a fixed modulation format are also explored.

The analysis highlights that significant benefits are brought by the flexible grid technique in efficiently accommodating traffic. Moreover, we show how the different algorithm strategies affect the utilization of network resources. Significant additional advantages brought by the MMF technique are also demonstrated.

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1 Introduction

In the following Chapter the motivations are contained in the first Section, the research method is the main focus of the second Section, while the third Section deals with the report outline.

1.2 Motivations

The main motivation behind this work is a deep interest in the evolution of optical communication systems and their on-the-field applications. As a part of a double degree project, the author based all his studies on optical networking. The author combined studies upon optical techniques at the Politecnico di Milano and studies on the Networking and Quality of Service Provisioning at NTNU (Norges Teknisk-Naturvitenskapelige Universitet), Trondheim, Norway. The thesis refers to a segment of telecommunication networks of relevant importance at the present time, such as the metropolitan networks.

1.3 Research method

The research method model which is adopted in this thesis is an academic adaptation of the deming cycle of a project proposed by the Project Management Body of Knowledge (PMBOK) [77]. The model of the deming cycle is reported in Figure 1.

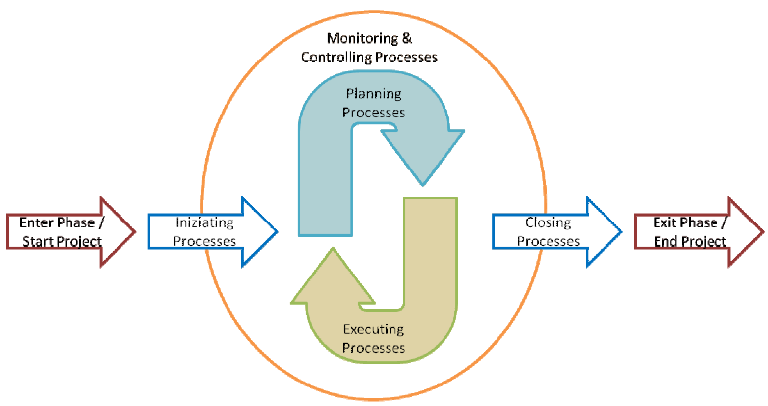

Figure 1. Deming cycle of a project proposed by the Project Management Body of Knowledge

Each step of the analysis his introduced according to the results obtained by the previous steps; each step is made of a planning and modeling phase, followed by an executing process. Monitoring and controlling processes consist of checking the coherence of the model elaborated and analyzing the obtained results. Such results will be the core of the subsequent initiating process. The closing process coincides with the end of the work but, as suggested for further works, a research and development process can never be considered closed.

1.4 Report outline.

The thesis is organized according to the following structure:

- [x]. Chapter x
    - [x].[y] Section y of Chapter x
        - [x].[y].[z] Subsection z of Section y of Chapter x

The rest of the thesis is organized as follows:

In **Chapter 2** the metro gap problem is presented, together with the definition of a metro network. An overview and comparison of the metro solutions which have been applied so far is provided.

In **Chapter 3** the flexible grid as evolutionary solution for the DWDM technology is introduced. The MMF capability is described. The network model and the assumptions which are adopted along the thesis are presented.

In **Chapter 4** the RSA algorithm is proposed. A detailed description of the policies which are provided to the algorithm as input are described. The metrics used to evaluate the performance of the algorithm through simulations are enlisted.

In **Chapter 5** the benefits brought by the flexible grid solution, if compared with traditional DWDM technology, are presented. Simulations for a ring topology exploiting flexible grid technique and a fixed set of policies as input are carried out. Hence the obtained numerical results are compared with the performance of a DWDM.

In **Chapter 6** how the policies chosen for the RSA algorithm affect the network performance is analyzed. Simulation for a ring topology exploiting flexible grid technique and varying the set of policies provided to the algorithm as input are carried out. The obtained numerical results for different policies are compared.

In **Chapter 7** the additional benefits of the MMF capability, if compared with a network exploiting a fixed modulation format, are explored. Simulation for a ring topology exploiting flexible grid technique and MMF capability are carried out. The set of policies provided to the algorithm is varied. The obtained numerical results are compared with the performance of a equivalent flexible grid network but without MMF capability.

In **Chapter 8** the conclusions and the proposed future works are presented.

2. Overview and comparison of existing metro solutions

In this Chapter the reader is introduced to metro network architectures and their evolution. The requirements to be satisfied in principle are outlined, the role of the metropolitan segment is inserted into the whole internet scenario and legacy technologies are explored. In detail, SONET/SDH, Ethernet, Resilient Packet Ring and Metro Ethernet Network are explored from Section 2.2 to Section 2.5; a comparison of the costs these solution involve is presented in Section 2.6. Some experimental systems that have been presented to the manufacturers are explored in Section 2.7. In conclusion, in Section 2.8 the promising innovation of metro networks exploiting elastic transponders as well as Multiple Modulation Format are presented.

2.2 Guidelines of the evolution of metro networks

As the load of traffic circulating through networks grows rapidly, a proper utilization of the available bandwidth is a key factor for service providers in order to survive into the market. This is particularly true where employable bandwidth is a resource present in scarce amounts, hence expensive. It is the case of metro networks.

In such densely populated areas, as metropolitan ones, deployment of new fibers involves extremely high digging costs. This makes the spectrum offered by already deployed fibers a very valuable resource, whose utilization must be efficient in order to keep pace with bandwidth-hungry requests from clients.

In this Section we first quickly frame the "*metro gap*" problem, then we define properly what the term metro network refers to. Finally the features required to the networking technology into the metropolitan segment are enlisted; they represent the challenges that service providers have to face in developing new solutions for metro networks.

2.2.1 The metro gap

It is clear to everybody how the internet has gained a role of great importance in modern society. Bandwidth-hungry applications are now flourishing every day, causing a constant growth of traffic over the transport networks. Based on the new all-over-IP paradigm followed by most of service providers, the data traffic represents the greatest traffic share. At the present time, it is foreseen that the annual global IP traffic will reach the zettabyte per year by the end of 2015 [1]. The expected trend of such traffic growth can be observed in Figure 2, where the traffic is expressed in exabytes per month; traffic milestones (blue boxes) and traffic generator milestones (right-hand side of the line) are also pointed out in the outline of the graph. A broadband access able to provide instant and high-speed access has important benefits to the society and becomes fundamental for residential and (small) business customers.

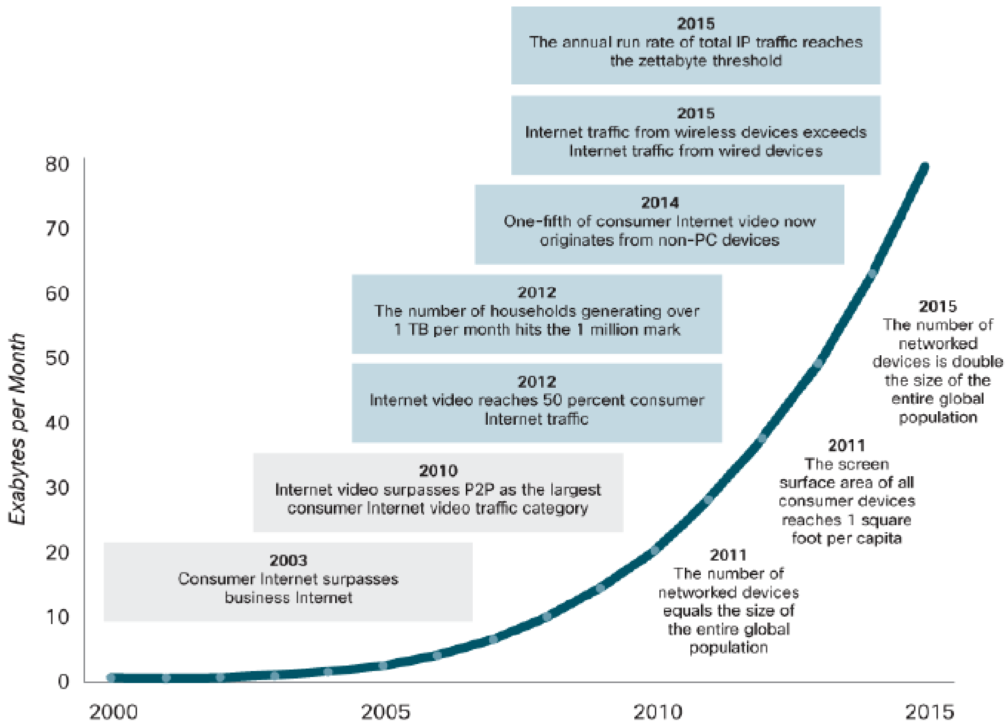

Figure 2. Expected global IP traffic growth (exabytes per month), five traffic milestones and three traffic generator milestones by 2015 (1).

In order to counterbalance this massive traffic growth, over the last decade the provided bandwidth has increased over 300 times in the backbone and 100 times in the access, but only a meager 16 times in the metro producing a significant metro bottleneck [2]. This bandwidth bottleneck is often referred to as 'metro gap' [3]. Due to the metro gap, high-speed end-users in the local segment might be prevented to access the wide amount of bandwidth available in the backbone.

2.2.2 Definition of a Metro Network into the Internet Scenario

According to the geographical span and the capacity of the links involved, the following three categories of networks were generally recognized in the 80s, at the beginning of Internet history [4]:

- WAN, Wide Area Network. Characterized by their use of local and long distance telecommunication facilities (telephone, microwave and satellite) for intermodal communication, their size ranged from local to regional or national. At the Internet dawning, transmission rates typically varied from 300 to 19.200 bit/s, occasionally as high as 56.000 bit/s. They interconnected up to several thousands of interfaces.

- MAN, Metro Area Network. Generally restricted to a metropolitan area, often just a city alone. They made use of CATV (cable television or, in the first meaning of the term, Community Antenna Television) and telephony systems. They could offer transmission rates common to wide area networks, but with a base of less interfaces
- LAN, Local Area Network. Initially lacking of a unique definition. They were predominantly single multi-access bus- or ring-oriented cables whose end-to-end length may approach 20 km, but which are typically within 5 km. Their topological scope could vary from intradepartmental to intrabuilding or intracampus, rarely exceeding this range.

This mentioned above was the first classification among network typologies based on transmission rates and geographical range. Nowadays, apart from the transmission rates on the links (that have increased exponentially) the distinction of the whole Internet transport network into these three segments still hold in great measure. Figure 3 is commonly used to summarize the network hierarchy from the optical networking perspective.

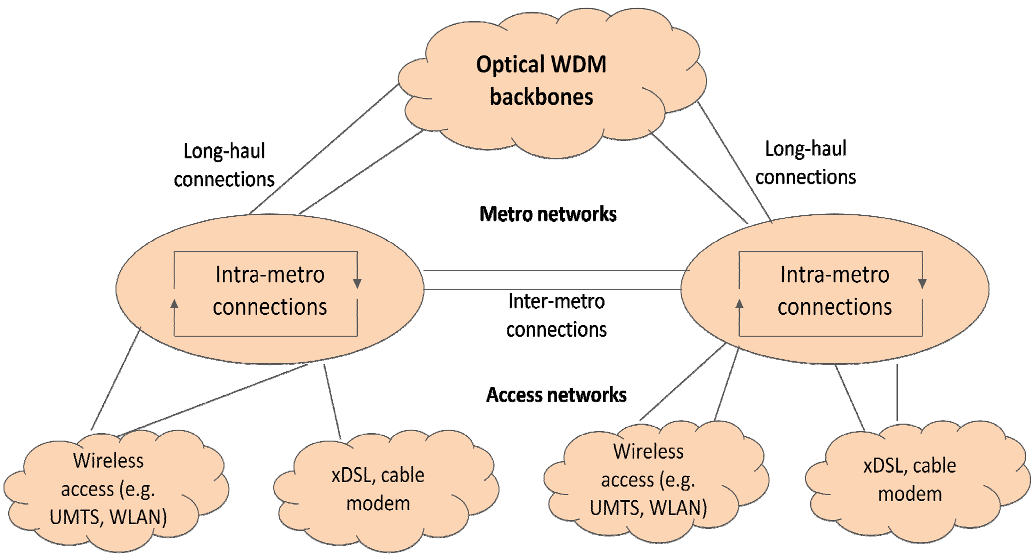

Figure 3. Network hierarchy.

Two main changes can be identified into how this distinction among the three network segments has evolved through time. First, the term WAN has been widely replaced by the more common terms Long-haul or, equivalently, Backbone or Core. But the most important change is the ingoing process of merging between MAN and LAN. The boundaries between MAN and LAN have become blurrier and blurrier. In the last evolution of PONs, Passive Optical Networks, the term MAIN has made its appearance among the network typologies. MAIN stands for Metro-Access Integrated Network and it is used when dealing with LR-PONs, Long Reach PONs. The latter is the fruit of the ultimate development of the PON (Passive Optical Network) technology. PONs have been so far the most successful solution able to provide optical access to the end customers and have all the features to be seen by the field experts as the most promising solution for the long-term future.

With the insertion of OADM (Optical Add Drop Multiplexer) and optical amplifier, LR-PONs extended the distance reach from the OLT (Optical Line Terminal) to the ONUs (Optical Network Units) up to 100 km and beyond. This reach has to be compared with the 20 km of traditional PONs.

The merge of the two network segments is beyond the scope of work. Here we focus on the sole metro segment. With metropolitan area network, or metro network for short, we refer to the portion that interconnects the backbone networks with local access networks.

In order to give a basis for comparison also with regard to the present bandwidth hunger, we refer the reader to [5] where a calculation of the required bandwidth per subscriber is carried out. As a result, a network capacity of circa 75 Mbit/s per subscriber should be guaranteed in order to accommodate triple-play service. The bandwidth estimation is summarized in Table 1.

Services	Bandwidth [Mb/sec]
Three HDTV Channels	60
Internet	10
Video Conference (Phone)	2
Telemetric/remote control	1
Total Bandwidth	**75**

Table 1. Estimated required bandwidth per user due to triple-play service (5).

2.2.3 Metro Network Requirements

According to what has been said so far, it looks obvious that enhancements has to be brought into metro networks. The main requirements that new technologies and architectures have to meet are [6]:

- *Capacity and scalability*. We mentioned above which is the expected bandwidth required by each subscriber (75 Mb/s). Exploitation of optimal network architecture and efficient transmission technology is obviously a key factor to enable a service provider to stay alive into the market.
- *CAPEX and OPEX*. Minimizing CapEx (capital expenses) and OpEx (operating expenses) is as always the main target of carriers in order to offer their services at a competitive and profitable price. Those consist of buying and installing equipments, their compatibility with previously operating systems, their adaptability to future solutions
- *Technical maturity and standardization*. They guarantee interoperability with other manufacturers.
- *Reconfigurability*. With the blooming of new IP-based applications, the nature of the traffic is going to be highly variable. It can be peer to peer dominant or mostly asymmetric (top-to-down, e.g. IP-TV); it can be intra-area (between access nodes belonging to the same metro network) or inter-area; the granularity can be rough or fine. The higher number of features the implemented solution can cover, the higher degree of success the solution will encounter.

- *Burstiness*. With the proceeding of the all-over-IP paradigm, traffic distributed inside the metro area will experience the bit rate variations characteristic of the IP traffic.
- *Resilience and QoS*. Different IP applications require different QoS constraints; being able to provide QoS differentiation is fundamental in order not to corrupt the customer trust. Resiliency becomes a very valuable feature of the network especially when the traffic flow on each link increases considerably, which implies that a network failure causes the loss of a huge amount of data.
- *Backward Compatibility*. In every field, evolution is never carried out into a single sprint but rather with progressive steps. An innovative solution which preserves the already-deployed main devices allows carriers to reduce CapEx, and thus to make the solution doable.

2.3 SONET/SDH

In this Section the technology that played the role of undisputed leader in the metropolitan segment for a long time is introduced.

In the first Subsection the reasons of this success are brought to the reader. After that, a closer look to the technology is provided. Finally a detailed analysis of the limitations of SONET/SDH, together with some possible solutions, is given. We conclude this Section 2.2 showing how this technology is not a competitive path to be covered by service providers due to the decoupling of revenues from traffic.

2.3.1 Why SONET/SDH in MANs

We have defined in Section 2.1 that MANs are generally defined as the portion of network that interconnects the backbone networks with local access networks. Their concept thus inspired from the desire to communicate over a wider geographical area, they have been in existence for about two decades now. MANs have traditionally been designed for voice transmission based on time division multiplexing (TDM) technology. When first deployed, voice was the predominant traffic being carried through the network [7].

As a result, SONET/SDH became the dominant standard in the metro areas. With regard to the physical configuration that MANs present at current time, it is common to find a fiber plant with a planar mesh structure (fiber routes do not cross, except in the metro centers) [8]. Hence it is often straightforward to organize the metro network as a set of interconnected SONET/SDH rings. They also provide effective protection mechanisms against equipment failures, thanks to their fast failure detection and short restoration time. It prevents users from experiencing relevant traffic losses or long out-of-services periods due to failures; in certain cases, full connectivity within the ring can be assured even after multiple failures.

We thus have seen how voice traffic and ring as basic element of the network architecture have driven SONET/SDH as predominant technology for metro access networks. In the next Subsections we give a closer look to the technological fundaments of SONET/SDH technology, followed by the limitations of such solution due to the evolution of traffic nature and expected revenues in the last two decades.

2.3.2 The SONET/SDH technology

SONET/SDH is a circuit switched networking technology. SONET (Synchronous Optical NETworking) was introduced in 1984 by Telcordia and, in 1988, the American National Standards Institute (ANSI) Committee T1 had published standards for SONET rates and formats, T1.105 [9], and for the optical interface, T1.106 [10]. SDH (Synchronous Digital Hierarchy) is standardized by Recommendations G.707 [11], G.708 [12] and G.709 [13] by CCITT (Comité Consultatif International Téléphonique et Télégraphique, later renamed ITU-T).

Thus SONET is the standard in use in USA and Canada, while SDH had been adopted in the rest of the world. The two standards are fully inter-operable. SDH is sometimes referred to as a superset of SONET, since all principle considerations apply to SONET too [14]. In the following, with SDH we are going to refer to both standards. When a feature that is peculiar to only of the standards is illustrated, it will be pointed out.

Their first goal of SDH was to replace the PDH (Plesiochronous Digital Hierarchy) technology, not able to handle large quantities of data. SDH is based on the synchronization of all the clocks belonging to the network. A Primary Reference Clock (PRC) is distributing his timing throughout the whole network by means of a master-slave architecture. This is accomplished by means of a Synchronous Status Message (SSM) carried by the SDH frame [15].

The reliable synchronization of the whole network to a single time reference enables the two basic principles that SDH is implemented on:

- Direct synchronous multiplexing of individual tributary signals within the structure of the higher-rate multiplexed signal
- Transparent transporting of each individual tributary signal through the network, without any disassembly except at the two network nodes that exchange information through that particular signal

The two features are summarized by the term “direct multiplexing approach”. It means that a single tributary signal can be inserted and removed into the SDH higher-rate multiplexed signal at any point into the network without the need of intermediate demultiplexing (disassembling) and multiplexing (assembling) steps. The structure of a transmission path in a SDH network can be thus illustrated as in Figure 4.

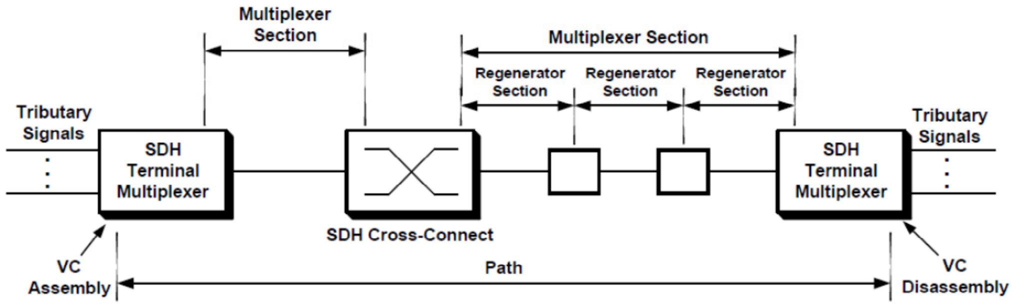

Figure 4. Structure of a transmission path in a SDH network.

The three basic Network Elements (NEs) of a SDH network can be noted in Figure 4. They are hereafter briefly described:

- SDH multiplexer (Terminal Multiplexer or Add/Drop Multiplexer). It performs the insertion/removal of tributary signals into SDH frames.
- SDH cross-connect. It permits to change the routing of tributary signals carried in SDH frames.
- Regenerator. It is used to increase the physical range of the transmission path.

Finally we mention how the data are framed into a SDH network. Three types of segments can be identified in the network:

- Multiplexer section. A part of a transmission path located between a terminal multiplexer and an adjacent SDH cross-connect equipment, or between two adjacent SDH terminal multiplexer
- Regenerator section. A part of a transmission path located between a terminal multiplexer or SDH cross-connect equipment and the adjacent regenerator, or between two adjacent regenerators. A multiplexer section can include up to three regenerator sections.
- Path (low-order path, high-order path). The logical connection between the point at which a tributary signal is assembled into its virtual container, and the point at which is disassembled from the virtual container.

A graphical representation of a typical transmission path in SONET/SDH is represented in Figure 5.

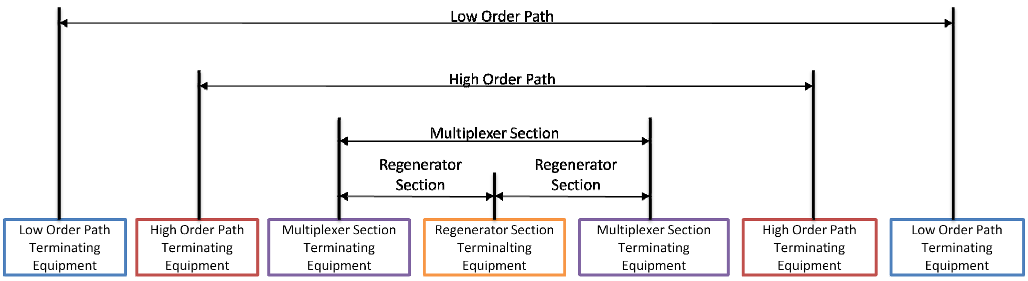

Figure 5. A transmission path in SONET/SDH.

Each of these segments is provided with its own overhead data, in order to provide the support and maintenance signals of the data transmitted across the segment. Without entering into further details, in Figure 6 it is illustrated how overhead data are organized in a STM-1 frame, that is the basic transmission format for SDH (155.52 Mbit/sec). The overheads related to the three types of segments described above are highlighted in different colors.

By using the overhead bytes, maintenance and protection is provided to all the segments. Out-of-normal conditions are detected by the maintenance means built into the SDH frames. Alarm and Indication Signals (AISs) are thus flowed in order to embank their consequences upon users' traffic. They all together constitute the most attractive feature of SDH technology: SDH networks are highly reliable. They present a restoration time in the range of 50 msec. That, together with their circuit-switched nature, made of SONET/SDH ring networks the choice of most of the carriers operating in metropolitan areas. Individual nodes access the network bandwidth in a TDM fashion, that is, each node is periodically allocated a specific number of slots.

SDH technology may also be combined with WDM in order to establish multiple SDH rings on one single fiber. In addition, by employing optical bypass of transit nodes and traffic grooming, it is possible to reduce the computational power as well as the number of electronic port cards at bypassed nodes. Traffic grooming has here been intended as the routing of traffic destined to a node on the wavelengths that are not bypassed at the node.

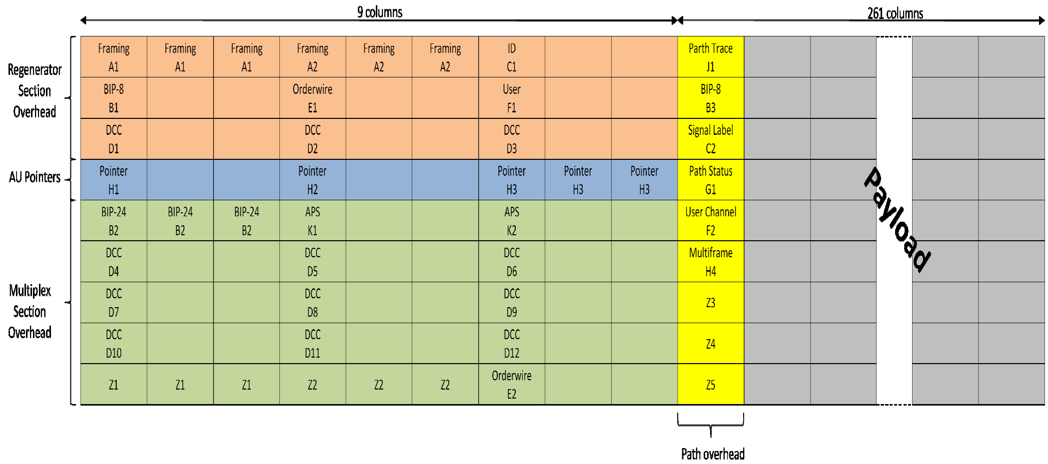

Figure 6. STM-1 frame format.

2.3.3 SONET/SDH drawbacks and possible solutions

In a metropolitan scenario in which voice represents the dominant traffic typology, circuit-switched SONET/SDH ring played the role of leading technology in MANs. But the undergoing shift of metro traffic from voice-centric to data–centric [16] brings to surface all the limitations of a SDH-based metro network. Optimized for slow-growing, narrowband, circuit-switched voice traffic, SDH ring infrastructures lack the dynamic functionality and rapid scalability to keep pace with the increasing volumes and unpredictability of data traffic. The circuit set-up time in a SDH network is on the order of several weeks or months [17].

This shift is true not only with regard to the wired telephony vs IP traffic, with an increasing number of companies in the telephony area that committing themselves to using the voice over IP (VoIP) technology [18] [19]. Also the mobile traffic, that has always been domain of voice traffic only, is undergoing this shift. With the developing of advanced mobile devices such as 3G handsets (the iPhone, the Blackberry, laptop cards and other PDAs, Personal Digital Assistants) IP traffic out of cell towers is being driven toward a huge increase. It is foreseen that in 2015 the amount of traffic exchange of a single mobile subscriber could very conceivably be 450 times what it was 10 years earlier in 2005 [20]. The bulk of this expected traffic will be made up of Video and Data, followed by P2P, as it is showed in Figure 7.

VoIP traffic is forecasted to be 0.4% of all mobile data traffic in 2015. Detailed forecasted data are reported in Table 2.

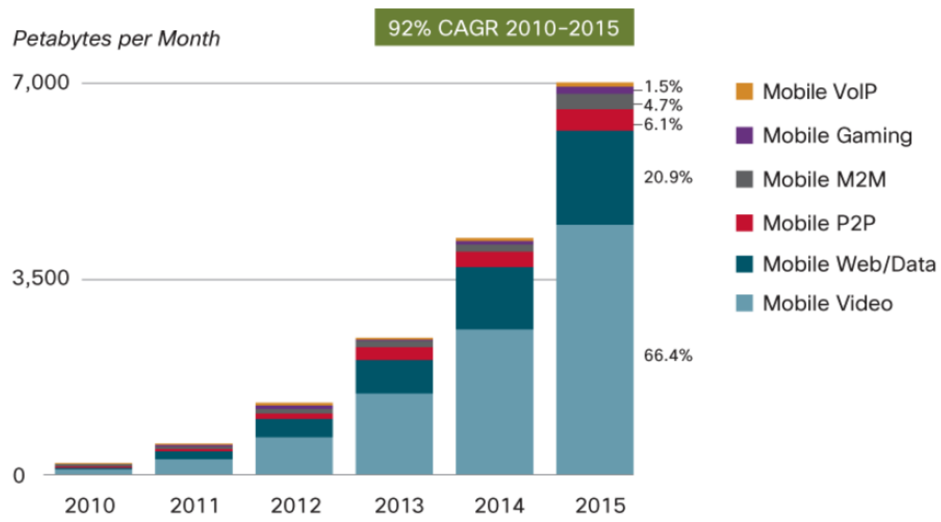

Figure 7. Global mobile data traffic forecasted for years 2010-2015 (20).

Application category	2010 [TB per month]	2011 [TB per month]	2012 [TB per month]	2013 [TB per month]	2014 [TB per month]	2015 [TB per month]	CAGR (Compound Annual Growth Rate) 2010-2015
Data	73,741	160,101	321,036	561,242	893,330	1,407,000	80%
File sharing	33,510	64,186	64,186	176,657	258,727	378,559	62%
Video	117,943	288,405	288,405	1,334,333	2,452,898	4,149,610	104%
VoIP	4,021	6,120	9,067	11,797	14,386	23,282	42%
M2M (machine-to-machine)	7,462	27,234	63,575	113,509	186,603	295,469	109%
Total Mobile Data traffic [TB per month]	236,676	546,050	1,162,950	2,197,563	3,805,989	6,253,991	92%

Table 2. Detail of forecast mobile data traffic with traffic sorted by application category (20)

As a conclusion, due to the shift towards data (all-over-IP paradigm), SDH shows all its limitations when accommodating packet traffic:

1. Rates only highly discrete: in units of STS-3c's (or STM-1s equivalently). Can't do STS-2c's
2. Entire payload on one path. No splitting, no multipath
3. Size mismatch: 10 Mb/s over 51.84 Mb/s, 100 Mb/s over 155 Mb/s, 1 Gb/s over 1.24 Gb/s. Inefficient transparent connections.
4. Data is bursty (dynamic). SDH is fixed (static)
5. Only one type of payload per stream: TDM, ATM, FDDI, Packets, Ethernet, Fiber Channel.

These inefficiencies are addressed by three new technologies, the so-called Data over SONET/SDH (DoS) technologies, which mitigates the burden of the drawbacks. Those technologies are Generic Frame Procedure [21], Virtual Concatenation [11] and the Link Capacity Adjustment Scheme (LCAS) [22]. With Virtual Concatenation multiple SONET low-data-rate connections are virtually combined (concatenated) into an aggregate connection close to the desired data rate. Virtual Concatenation thus provides data rates of much finer granularity in order to reduce the stuffing overhead. It thus put up the solutions here listed (to be noted that the solutions provided are numbered according to the limitations enumerated above):

1. A channel can be n* STS-1 or n* T1 for any n

2. Different STS-1's can follow different path

3. Size match: 10 Mb/s over 7 T1, 100 Mb/s over 2 STS-1, 1 Gb/s over 21 STS-1. When LCAS is added, further flexibility is obtained. The aggregate data rate can be adapted to the data rate currently required. Thus LCAs it provides for the following solution:

4. It can dynamically change number of STS-1's

Finally, the GFP technology remedy to the inefficient accommodation of data packets in SDH frames, hence it also addresses the limitation listed above as third. Until the GFP recommendation, many network operators used proprietary technologies for this purpose. Those required highly process-capable devices, since each incoming byte had to be monitored to recognize the boundaries of the variable-size data packets. GFP adds these solution at the Next Generation SONET/SDH:

5. Efficient Transparent Connections

6. It allows multiple types of payload per stream

2.3.4 Cost of SONET/SDH in metro areas

In the previous Subsection, along with the drawbacks of the SDH technology due to the shift of traffic from voice-centric to data-centric, we have also presented that solutions have been provided in order to enhance SDH rings to accommodate variable-size data packets.

Nevertheless, such solutions leaves unvaried the first and most important drawback of this technology: SDH was introduced as a circuit-switched networking technology and, as such, does not fit as efficient solution for carrying packet traffic. In addition to the drawbacks listed above, we can also note SDH was designed for symmetric traffic, while in metro areas we find strongly asymmetric IP traffic. This is true especially with triple-play service coming into the game.

The most immediate and penalizing consequences concern with costs. In SDH ring networks, the addition of supplementary bandwidth increases linearly with the bandwidth provided. This was acceptable into a voice-centric market, but into a data domain STM-n's lines are not a suitable solution anymore because to an exponential growth of traffic they answer with an exponential growth of costs as well. This scenario is illustrated in Figure 8

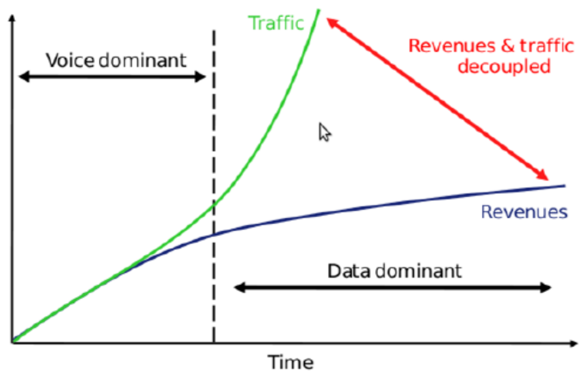

Figure 8. Decoupling of revenues from traffic into a data-dominant scenario.

This is why telecom operators have already started a process of introducing new technologies into metro networks in order to keep pace with the market requirements. Other solutions are taking over the role of leading technology into metropolitan areas.

2.4 Ethernet

It has been presented to the reader in the previous Section 2.2 that SONET/SDH has traditionally been the dominant standard in metro networks and how, due to the explosion in the demand for bandwidth for data transmission, it does not fit anymore with its circuit-oriented way of handling traffic. Which is then the most suitable solution to overcome SDH limitations?

The answer lies into the access segment: according to the Metro Ethernet Forum [23], in 2004, 98 percent of all data traffic in all enterprise LANs start and end on a Ethernet port. Hence, it is a natural consequence to look at Ethernet as the technology able to fit the best also in a metro geography. But of course the step of introducing Ethernet is not as straightforward as it might seem.

Ethernet is thus presented into this Section 2.3. We explore in the first Subsection the recent growth of this technology that lead to associate the adjective ubiquitous to this solution; then a quick view to the protocol stack is provided. In the last Subsection, the main challenges of introducing a technology conceived for LAN applications into a metropolitan scenario.

2.4.1 The Ethernet technology

The Ethernet standard (IEEE 802.3) [24] is a physical layer and MAC layer transport protocol designed in the 70's for supporting cheap LAN applications. Until the mid 1990s, other LAN technologies coexisted with Ethernet (e.g. token ring, FDDI, …). However, Ethernet succeeded in becoming the dominant LAN technology for companies as it quickly adapted to upcoming requirements:

- Planning reliability
- Future proof hardware

- Easy management. That is plug-and-play capabilities, scalability with respect to network size and link speed as well as simple migration.

In the mid/late 1990s Ethernet enforced its position of predominant technology in the LAN geography with its fast bandwidth evolution while maintaining backward compatibility. In Figure 9 a snapshot of the bandwidth growth experienced by the Ethernet is provided.

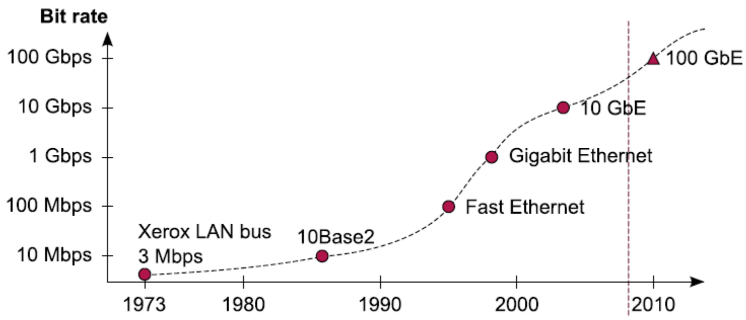

Figure 9. Growth of Ethernet bit rate.

Another key factor that laid the fundamentals of Ethernet successful story has been its support towards the interconnection if wireless technologies, e. g. IEEE 802.11 compliant WiFi [25]. This boom in adopting the Ethernet solution gave birth to the Ethernet-everywhere paradigm [26]; the paradigm is still leading many market main streams at the present time.

2.4.2 Ethernet Protocol Stack Overview

As stated into the previous Subsection, IEEE 802.3 is a physical layer and MAC layer transport protocol. Together with the IEEE 802.2 [27] and IEEE 802.1 [28] standards, they cover both the Data Link Layer (DLL) and the Physical Layer (PHY) of the ISO/OSI reference model [29]. With regard to the DLL, whilst the IEEE 802.2 defines the Logical Link Control (LLC) sublayer, the IEEE 802.3 standard defines the specifies the Media Access Control (MAC) sublayer. In the latter, the physical layer is specified as well. Finally, the specification of the bridge layer between MAC layers is part of the IEEE 802.1 standard. The Ethernet protocol stack including its functions is represented in Figure 10.

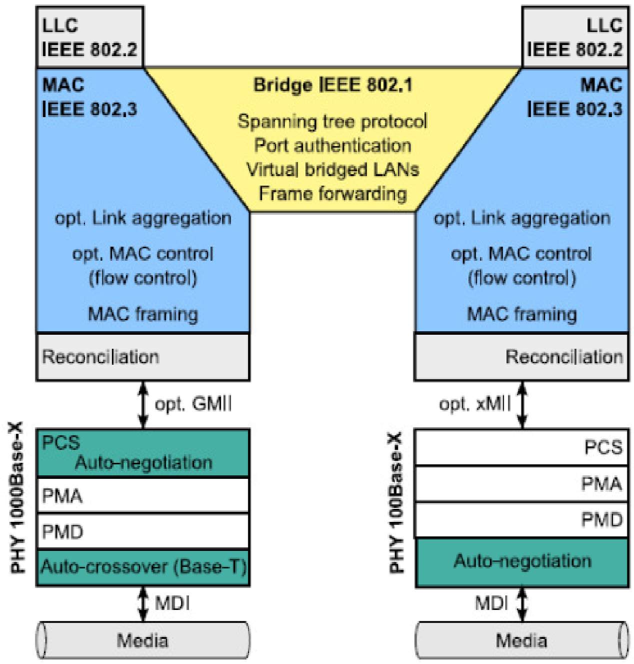

Figure 10. Ethernet protocol stack.

For a more detailed description of the functionalities of each layer, we refer the reader to [24], [27] and [28]. Nevertheless, we hereafter provide a quick insight of the auto-negotiation feature, key functionality in backward compatibility of Ethernet devices.

Such a feature is the ability of two interconnected devices presenting different line rates to agree on a common line rate. Auto-negotiation resides in the lower part of the PHY if copper cabling is used (on the right-hand side of Figure 10). Otherwise, for optical attachment units, the feature is embedded within the physical coding sub-layer (left-hand side of Figure 10).

The auto-negotiation process modulates link pulses exchanged on idle Ethernet links with line rate information. Upon reception of the pulses, both devices determine the common line rate and duplex mode.

2.4.3 Ethernet Drawbacks and Possible Solutions

Whilst Ethernet experienced a great success into LANs, the same cannot be said about the metropolitan area. The Ethernet technology clashes with two main limitations when adopted into a metro network:

- The convergence time of the Spanning Tree Protocol (STP).
- Lack of fairness in the utilization of the shared bandwidth.

Among the requirements of Metro Networks in Section 2.1, resilience has been mentioned. Thus we have seen in Section 2.2 how resilience is the strong hold for SONET/SDH rings. Recovery time is in fact a key parameter for resilience quality of a network.

The network recovery time is usually defined as the time it takes to detect a failure plus the time it takes to reconfigure the network so that communication is restored [30]. The recovery times obtained with SONET/SDH rings is about 50 msec. In STP, first specified in standard IEEE 802.1D [28], default detection is performed by means of special test packets arrival within a certain amount of time. Such time-out intervals are fairly large, so that Ethernet fault detection time can reach intolerable length peaks. When a fault is detected, it has to be reported to the root node of the complete tree topology of the network previous built. It is thus task of the root node to reconfigure the logical topology by flooding again the ring. The all process can last more than 60 seconds, which is absolutely an intolerable valuable for carriers in the metro area.

Over the years, many solutions have been proposed. Some fairness in bandwidth assigned is obtained by the introduction in the standard IEEE 802.1Q [31] of the Virtual LAN (VLAN) extension. It provides traffic engineering features and a certain level of security. The VLAN extension enables a virtual separation of multiple LANs on the same physical infrastructure.

With regard to the resilience, some proprietary solutions showed up in the market. Vendors proposed their own techniques able to shorten with a considerable magnitude the recovery time in Ethernet-based networks.

Examples can be brought up to the reader are the Cisco Resilient Ethernet Protocol (REP) [32] and the Ethernet Automatic Protection Switching (EAPS) [33] by Extreme Networks. One proposed solution is maybe more notable than the others. It is the RSTP protocol, where RSTP stays for the Rapid variant of the STP [34]. RSTP overcomes the main issue of proprietary solutions, that is interoperability between different vendors. This rapid variant claims performances within the 50 msec of SONET. Nevertheless, some controversy exists on the real RSTP performance. The general flavor of network engineers on RSTP is negative (e.g. the reader can refer to [35]), even though recent industrial reports express good performance [36] [37]. Next to the RSTP, another protocol which came to Ethernet's aid is the Multiple STP (MSTP) [38]. MSTP allows the simultaneous creation of multiple spanning trees or even backup spanning trees, which can substitute the current spanning tree in case of fault without the need of rebuilding a new one.

According to what shown so far, we have two valid solutions in metro networks: one well-know and traditionally successful thanks to its strong resilience, and another which brings many advantages in terms of costs and ease of management. The former is SONET/SDH, the latter is Ethernet. In both technologies efforts have been made in order to overcome their limitations, but an efficient trade-off between the two technologies seems hard to reach because of their natures. Circuit-switched for voice-centric traffic the SONET, hub or star topology in LANs with no traffic engineering the Ethernet.

2.5 Resilient Packet Ring

In this scenario a completely different approach has been undertaken by the IEEE 802.17 Resilient Packet Ring Working Group (RPRWG) [39]. Together with the IETF WG IPoRPR (IP over Resilient Packet Ring) [40], they are working on the new Resilient Packet Ring (RPR) standard for packet-switched metro ring networks.

As we have seen, neither SONET nor Ethernet is ideal for handling data traffic on a ring network. SONET does take advantage of the ring topology, but does not handle data traffic efficiently, wasting ring bandwidth. Ethernet, while a natural fit for data traffic, is in fact difficult to implement on a ring, and does not make the most of ring's capabilities. Packet Ring protocols have the advantage to approach the metro gap with the clean state. RPR thus promises the best of both worlds. Packet Ring protocols create a full, packet-based networking solution that avoids the provisioning complications and inflexibility of SONET and provides the ring protection and global fairness features missing from Ethernet.

We hereafter provide a quick overview of the RPR technology, with its main features that could represent key advantages into a metropolitan segment. We conclude this Section with a brief discussion over the reasons why RPR has not succeeded as expected on the first place.

2.5.1 Resilient Packet Ring Technology

Compared to legacy technologies, RPR has the key advantage of being independent from the underlying physical layer.

RPR is in fact a MAC layer technology, that is, RPR is independent of the physical layer. It can run on SONET/SDH, Ethernet and Dense Wavelength Division Multiplexing (DWDM). Integrating the high reliability of SONET self/healing and Ethernet advantages such as low cost, large bandwidth, flexibility and scalability, the RPR technology provides bandwidth management with data optimization capability and high performance multiservice transmission on a ring topology [42]. RPR works on a concept of dual counter-rotating rings called ringlets. The RPR network and node architecture is shown in Figure 11.

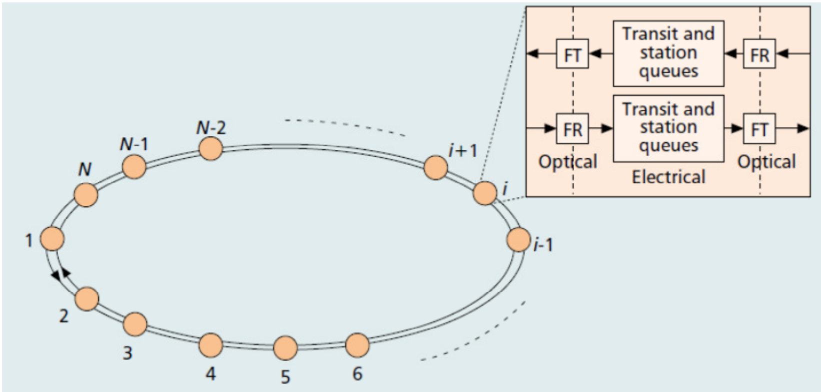

Figure 11. Scheme of a RPR network and a semplified node architecture.

RPR is an example of a buffer insertion ring where each node features three different types of buffers or queue: reception, transmission and insertion.

We mentioned above how RPR technology is independent from the underlying physical layer. It is thus important to point out that RPR is not intended to compete with SONET or Ethernet; it is complementary to both of them. Let us remind to the reader that RPR is a MAC protocol and operates at Layer 2 of the OSI protocol stack. By design, RPR is Layer 1 agnostic, which means that it can run over either SONET or Ethernet. RPR enables service providers to build more scalable and efficient metro networks using SONET or Ethernet as physical layers. In the next Subsection, we quickly present the main characteristic of the RPR standard. We refer the readers interested in such solution to [41], [42], and [43].

2.5.2 RPR Main Features

RPR has several features that make it a suitable platform for delivering of data services over a ring network, such as metro networks.

- Packet Add&Drop Multiplexing (ADM) architecture with bypass of transit nodes. It improves scalability while reducing the processing capability required at each node.
- Physical layer versatility. Packet Ring technologies will be compliant with Ethernet, SONET and DWDM physical layer standards

- Resiliency. The RPR standard mandates a restoration time below 50 msec. When the fault is detected, *wrapping* is performed at the nodes surrounding the cut, while all the frames in the network are *steered* in the only viable direction in order to reach the destination node.
- Topology discovery. It determines connectivity and the ordering of the stations around the ring.
- Bandwidth fairness. The RPR standard provides a bandwidth fairness algorithm. It operates in two different modalities: conservative or aggressive.
- Bridging. RPR supports bridging to other network protocols in the IEEE 802 family, and any station on an RPR ring may implement bridge functionality
- Broadcast and multicast traffic. For a multicast transmission, the nodes can simply receive the packet and forward it, until the source node strips the packet. For broadcast and multicast traffic, only one packet is sent through the ring.

2.5.3 Motivations Behind the Lack of Success of RPR

The initial perspective of RPR was a technology able to support carrier-class, service level agreement (SLA)-based metro Ethernet, IP, and legacy TDM services [44]. Such a promise gathered the attention of many vendors, but it can now be said that the technology has not reached the expected success yet. In document [45] RPR is listed as a failure in favor of Carrier Ethernet (which will be introduced in the next Section).

It has been said that RPR is a MAC layer technology. It thus introduces a new MAC header, which is not compatible with ubiquitous Ethernet. Moreover, a new set of complex protocols and algorithms (listed above, topology discovery, bandwidth fairness, etc.). These features contribute to RPR complexity and development/deployment cost, and thus lack of economic viability [46].

There is also another interpretation for the lack of success from RPR which recognizes the losing factor of RPR towards Carrier Ethernet into a bad choice of timing from the former. In [47] it is said by the analyst David Dunphy: "Even the best solution might not succeed if it comes to market after a less compelling alternative that had better timing". In Table 3, the timeline of RPR is presented, compared to that of Metro Ethernet. When RPR first appears into the market, some vendors has thought the void was already filled.

RPR timeline	Metro Ethernet timeline
December 2000: IEEE 802.17 Working Group formed	June 2001: Metro Ethernet Forum formed
March 2001: Objectives defined	August 2001: technical committee launched
July 2001: consolidated technology proposals	October 2001: Technical specifications for architecture, Ethernet services and protection in MANs defined
March 2002: proposal draft	
August 2002: first draft	October 2003: The Metro Ethernet Forum ratified the industry's first standard for metro Ethernet service
September 2004: final standard	

Table 3. RPR vs Metro Ethernet timeline

2.6 Metro Ethernet Network

In Section 2.3 we have seen how Ethernet does not make the best of ring topology. Though well suited for point-to-point and mesh network topologies, it is difficult to deploy Ethernet in ring configurations and as a shared media. Rings act as a shared media and need MAC mechanisms to manage access across multiple users. Ethernet has evolved to support full-duplex switched infrastructure and lacks this MAC. We have seen in Section 2.4 how RPR technology obviates to this issue by defining a Ethernet-compliant MAC standard and how such solution has not fulfilled the expected success. As anticipated at the end of the last Section, hereafter we are going to present to the reader another approach: the Metro Ethernet Networks (MENs).

How a MEN is defined is the focus of the first Subsection. Here we find the two basic approaches to make Ethernet a suitable technology also in carrier networks: Ethernet services and Ethernet transports. The latter is closely treated in the second Subsection.

2.6.1 What is Metro Ethernet Network (MEN)

A Metro Ethernet Network is generally defined as the network that bridges or connects geographically separated enterprise LANs while also connecting across the WAN or backbone networks that are generally owned by service providers. The MENs provide connectivity services across metro geography utilizing Ethernet as the core protocol and enabling broadband applications [48].

Deploying Ethernet in the metro is task of the Metro Ethernet Forum (MEF) [23]. The MEF, as the defining body for Carrier Ethernet is a global industry alliance comprising more than 150 organizations including telecommunications service providers, cable MSOs, network equipment/software manufacturers, semiconductors vendors and testing organizations. The MEF's mission is to accelerate the worldwide adoption of Carrier-class Ethernet networks and services. In MEF specifications, Carrier Ethernet is defined as a ubiquitous, standardized, carrier-class Service and Network defined by five attributes that distinguish Carrier Ethernet form familiar LAN based Ethernet:

- Standardized services
- Scalability
- Reliability
- Quality of Service
- Service Management

The five attributes are represented in the well-known Figure 12 by MEF. The current MEF technical committee is currently focusing their work on five key areas of technical development work. These areas are management, architecture, protocols/transport, services and testing.

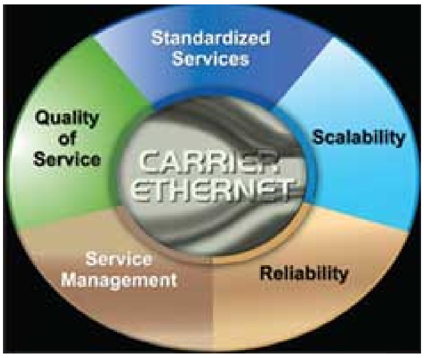

Figure 12. Five attributes that distinguish Carrier Ethernet from traditional Ethernet.

There are two basic approaches to introduce Ethernet into carrier networks. On the one hand, *Ethernet services* describe an Ethernet based interface to corporate customers who purchase connectivity between different sites as a transport service. Hence Ethernet services describe the transparent transport of Ethernet frames through operator networks. In this scenario operator networks differ from LANs as the latter rely on Ethernet also for the physical layer. Specification of such services are proposed by the MEF and differentiate between port-based Ethernet (E) services and Ethernet virtual (EV) services. The ground of the latter is given by different VLAN tags. Proposed service topologies include point-to-point E-Line (EV-Line) services, multipoint-to-multipoint E-LAN (EV-LAN) services and E-Tree (EV-Tree) services. A wide range of technologies are able to support Ethernet services.

On the other hand, *Ethernet transport* stands for a class of new packet-oriented transport technologies intended to replace traditional transport networks like SONET/SDH. We are now going to dwell on Ethernet transports; for the readers interested in Ethernet services, we refer to [49].

2.6.2 Ethernet Transport

Here below we recall which are the main shortcomings of native Ethernet, as already mentioned in Subsection 2.3.3:

- Architecture scalability. The MAC addressing scheme is not scalable to a wide-area environment. Its address-learning method, based on flooding, also does not fit.
- Resilience. Although STP was superseded by RSTP and MSTP, those developments still fall short of expected MAN and WAN protection speeds.
- Traffic Engineering (TE). Native Ethernet requires no traffic engineering and management. Such TE capabilities are among the fundamental aspects of carrier technologies because they enable QoS guarantees.
- OAM. Designed for LAN operation, traditional Ethernet lacks of capabilities for network configuration, equipment maintenance and performance monitoring.
- Security. For proper MAN and WAN functionality, Ethernet requires integrated security enhancements to address issued such as flooding. Traffic separation is needed, VLAN-tagging is too constraining.

We also mentioned how basic principles of Ethernet enable simple set up and operation of LANs, but are inappropriate to fulfill the stated requirements. Therefore interventions of MEF operate into two main directions: frame format and operations, and OAM and control. We are going to see them separately here below.

- **Frame format and operation**. One of the fundamental enhancements is brought by the provider bridging (PB) extension IEEE 802.1ad [50]. It allows the stacking of VLAN tags, i.e. the introduction of a second, so-called service VLAN tag (S-VID) in addition to the customer VLAN tag (C-VID). With only one tag permitted in a frame, when the customers already use VLANs in their networks, then a carrier is prevented from adding a VLAN tag for customer separation. With PB extension, carriers can define VLANs within their transport networks independently of customer VLAN assignment. Those extensions of the Ethernet frame format are illustrated in Figure 13.

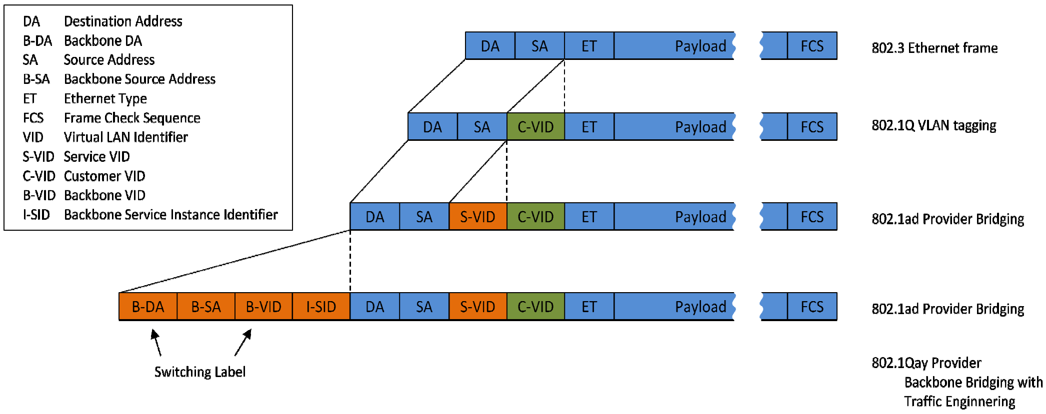

Figure 13. IEEE 102.1ad Provider Bridging extensions.

In Figure 13, we can also observe a second extension to the frame: the provider backbone bridging (PBB) extension 802.1ah [51]. It consists of the backbone Ethernet addresses, B-DA and B-SA. This external header contains backbone MAC addresses assigned to edge nodes of the PBB network, indicating the ingress and egress point of the frame in the PBB network. Hence, only the backbone addresses are visible inside the carrier network, providing a remedy to the scalability issues due to the flat addressing scheme. In addition, a 24-bit service identifier (I-SID in Figure 13) allows the differentiation of a larger number of customers. Still in Figure 13, it can be noted the presence of a switching label made of the backbone destination address together with the backbone VLAN tag. The switching label is part of the work of the IEEE WG 802.1Qay [52]. This group defines connection-oriented operations in carrier Ethernet networks using the PBB frame format, dubbed PBB-TE (Traffic Engineering). Frames are forwarded along Label Switched Paths (LSP) configured by the management plane of a future control plane. Due to the possibility to define multiple paths between any two network nodes, PBB-TE enables protection switching and traffic engineering. Finally, in addition to the protocol extensions, the IEEE defined Ethernet PHYs for carrier networks. They feature high data rates (work on 100 Gb/s is ongoing) and extended link ranges up to 40 km and beyond.

- **OAM and control**. In order to supervise the network and to quickly detect and localize failures, OAM features are required. In 802.1ag [53], connectivity fault management (CFM) messages are define. They include continuity check to test an existing path, loop back check to localize a failed link, and link trace to identify the bridges on a given path. Ethernet OAM can be deployed on several hierarchies, e.g. end-to-end and on individual path segments. A regulation of this hierarchy is found in ITU-T Recommendation Y.1731 [54]. In Y.1731 are also specified protocols for loss, delay and throughput measurement. With regards to the control plane, connection-oriented operations by means of LSP rely on centralized management systems. It is the case for Carrier Ethernet too, even though a future control plane based on ASTN/GMPLS (automatically switched transport network and generalized multi-protocol label switching, respectively). We can thus conclude that the centralized control of Ethernet transport networks in combination with service contracts giving way to traffic shaping at the network edges enable QoS guarantees. Assuring an appropriate ratio of reservations to available resources allows guaranteeing the bandwidth offered to a customer and an upper bound for latency.

The road to carrier-grade Ethernet is briefly summarized in Figure 14. The final goal of Carrier Ethernet is to match the SONET/SDH benchmark for availability (the five 9-s, 99,999%) and restoration time (50 msec) that, together high degree of network scalability, security, traffic engineering and OAM operations, can make Ethernet a suitable technology also for MANs and WANs.

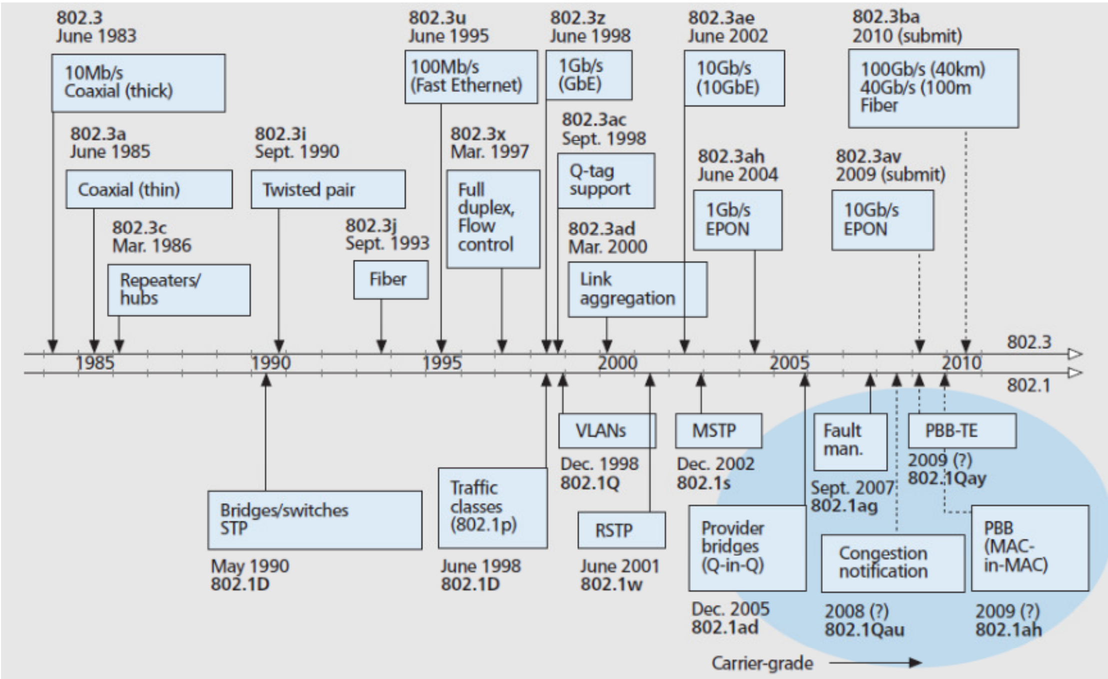

Figure 14. Timeline of Carrier Ethernet deployment.

2.7 Experimental systems for MAN rings

In the previous Sections we have described the different standardized technologies that played an important role so far in the metropolitan market and that are going to contrast each other in playing the role of leading solution for the future. In this Section, we are going to present three recent experimental testbeds for packet-switched ring metro WDM networks. Their names are KomNet, RINGO, and HORNET. The spotlight will be upon the physical architecture and node structure.

2.7.1 KomNet

The KomNet [55] network consists of a bidirectional fiber ring topology interconnecting three OADMs (optical add-drop multiplexer). In Figure 15 the structure of an OADM. The wavelengths to be dropped are reflected back into the 3-ports circulator by deploying the tunable fiber Bragg gratings (FBGs). The circulator takes them off the ring and directs them into the demultiplexer. Utilization of wavelength-insensitive combiners allows addition of multiple wavelengths in each fiber. The FBGs can be mechanically tuned within the millisecond range. We can then conclude the KomNet is well suited for circuit switching but, due to the relatively large tuning time of each FBG, this experimental system is inefficient for packet switching.

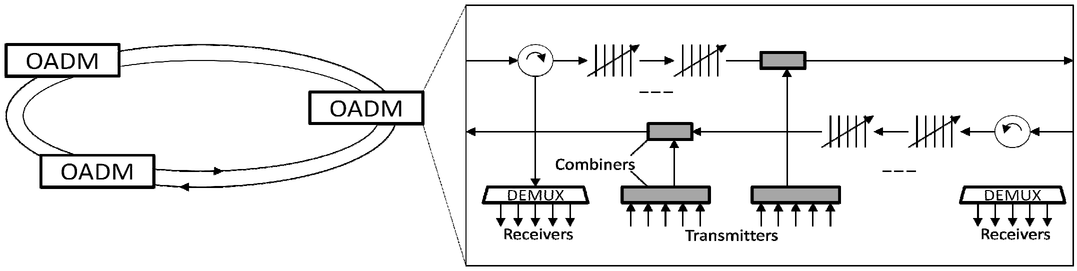

Figure 15. KomNet metro WDM network.

2.7.2 RINGO

Differently from KomNet, the RING optical network (RINGO) [56] solution we hereafter present has packet-switching as fundamental ground. It has an unidirectional fiber ring network architecture comprising N nodes, where N also equals the number of wavelengths. As we can see from the RINGO network representation in Figure 16, each node is equipped with an array of fixed-tuned transmitters and one fixed-tuned receiver operating at a given wavelength. The wavelength identifies the node into the network, that is node j drops wavelength λ_j such that, if a node has to transmit data to node j, it has to use the laser operating at wavelength λ_j.

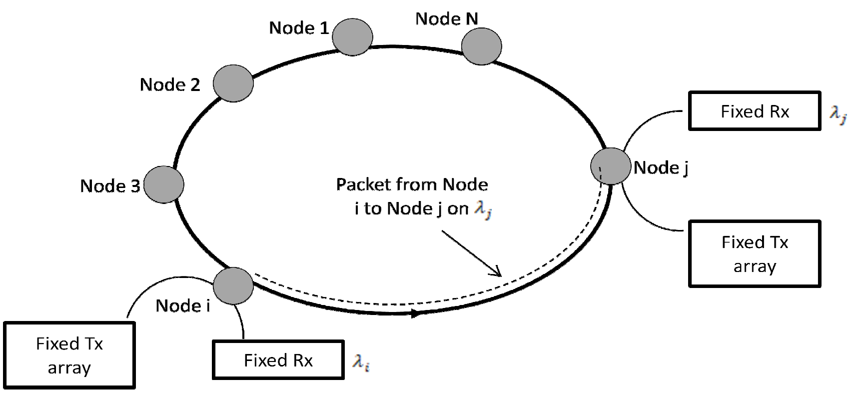

Figure 16. RINGO metro WDM network.

The wavelengths are slotted. The duration of a slot equals the transmission time of a fixed-size data packet, plus guard time. An empty-slot approach is used for transmission. A node that is not the destination node is only allowed to use empty slots for its transmissions. The structure of a RINGO node is represented in Figure 17.

In a given node j, the wavelength λ_j to be dropped is routed to a burst mode receiver, which recovers the clock for each optical burst (packet) very quickly; it does not require to receive a continuous signal. With regards to the other wavelengths, λ-monitoring is performed by means of 90/10 optical taps. Ten percent of the optical power is split off from the fiber and directed to a photodiode; the state of the wavelength occupation is checked and waiting packets, if any, are transmitted into empty slots.

Subsequently, the wavelengths are multiplexed on the outgoing ring fiber. With a 50/50 combiner and an external modulator, the node is able to send data packets by activating one or more fixed–tuned transmitters. Activation takes place upon instruction of the λ-monitoring photodiodes. The 50/50 combiner has two signal has inputs and equally combines them into the output port. It thus implies a 3dB combining loss.

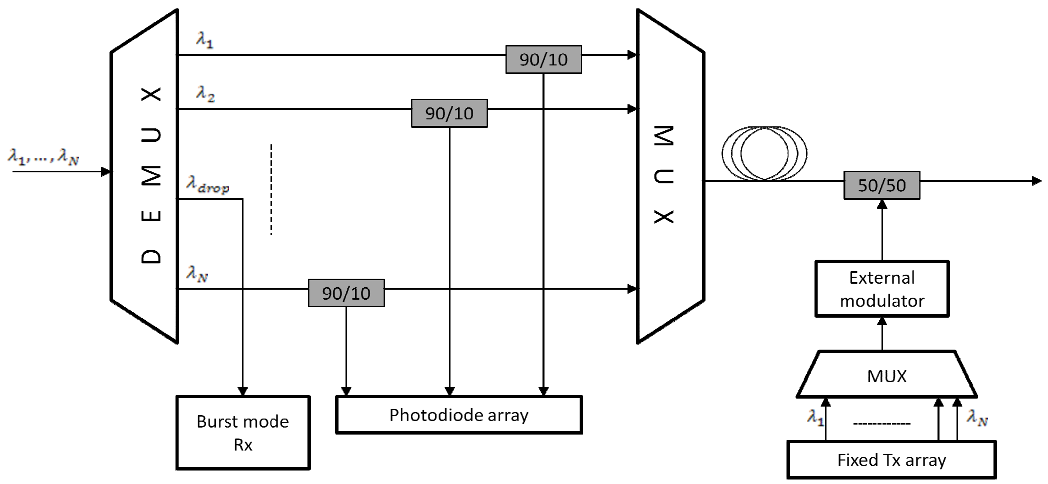

Figure 17. RINGO node structure.

2.7.3 HORNET

As the RINGO network, also the architecture or the Hybrid Optoelectronic Ring NETwork (HORNET) [57] consists of a unidirectional WDM ring. All wavelengths are slotted with slot duration equal to the transmission time of a sized-size packet, plus guard time. Differently from RINGO, in HORNET each wavelength is shared by several nodes for data reception. At each node is present one fast tunable transmitter and one fixed-tuned burst mode receiver. The node structure is organized into three sub-structures, or modules: a slot manager module, a smart drop module, and a smart add module. The HORNET node structure can be observed in Figure 18.

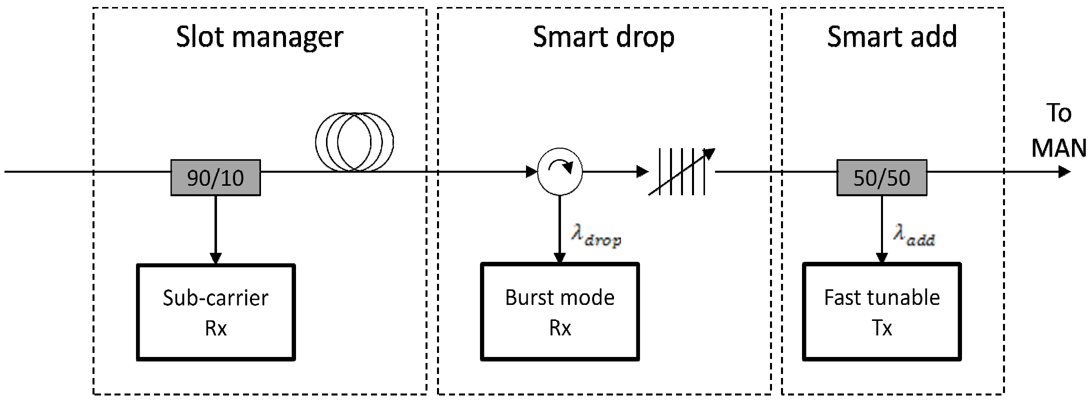

Figure 18. HORNET node structure.

A Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocol is used to govern the access to all wavelengths. When a node transmits a packet, it multiplexes a subcarrier tone onto the packet at a sub-carrier frequency that corresponds to the wavelength on which the packet is sent. Using a combination of amplitude shift keying (ASK) and frequency shift keying (FSK), the destination address of the sent packet id modulated onto the sub-carrier multiplexed (SCM) tone. It is duty of the slot manager module, whose structure is represented in Figure 19, to taps off a small amount of optical power (e.g. ten percent as for RINGO) and detect it with one photodiode.

By means of a collection of bandpass filters (BPFs in Figure 19), the composite SCM signal is demultiplexed into the single SCM tones. Whereas the SCM tone corresponding to the drop wavelength is FSK-demodulated, the remaining SCM tones are ASK-demodulated. With the ASK-demodulated tones the node achieves to know the state of the wavelengths occupation. If a slot is sensed free, an eventual packet queued on that wavelength is transmitted. The outcome of the FSK demodulation indicates whether there is a packet on the node's drop wavelength. It also gives the destination address of such packet. The sensed data is thus taken off by the smart drop module by using FBG, circulator and burst mode receiver. In case the destination address matches with the node's address the packet is pushed up to the upper layers of the node stack. Otherwise it is forwarded using the smart add module.

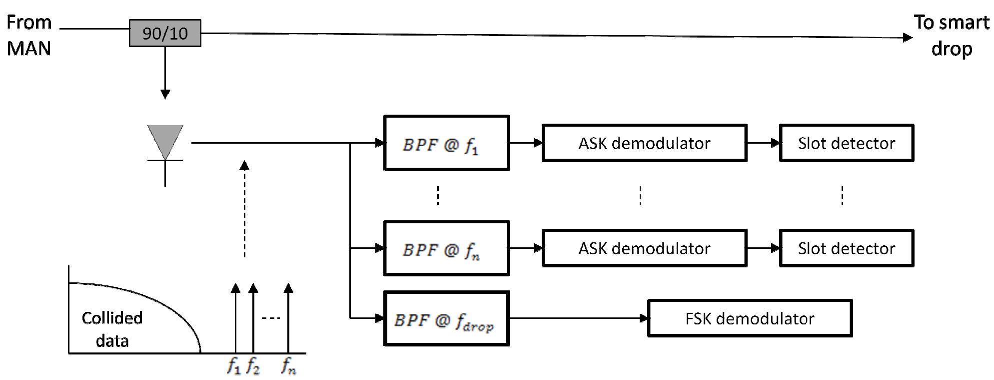

Figure 19. HORNET slot manager module structure.

2.8 Cost Comparison: SONET/SDH, RPR, Metro Ethernet

After a brief introduction to the metropolitan segment of Internet networks in the first Section, we have explored in Sections 2.2 through 2.6 the technologies that have worn the role of leading characters so far, with a quick hint to experimental solutions that have gained some particular attentions. Of all these technologies, the focus has been laid upon the technological aspects, with only little or no mention to the economical aspects they imply. In this Section 2.7 we try to provide some figures about differences in costs among SDH, RPR and Metro Ethernet. In the first Subsection, the economical impact of the initial deployment is taken into consideration, while in the following Subsections different increments of users and per-user bandwidth are considered.

2.8.1 Initial deployment

A typical SONET/SDH network, from the end customer to the Point of Presence (PoP), has the architecture shown in Figure 20. T1, T3 and OC3 interfaces provide respectively DS-1, DS-3 and OC-3 connections to the end users. In the representation we associated DS-1 to home users (Fiber-To-The-Home solution), DS-3 are foreseen to connect a building (Fiber-To-The-Curb or Fiber-To-The-Building solution) while business corporate are served by OC-3. Add&Drop Multiplexers (ADMs) switch intra-ring traffic, hub can be addressed to both intra- and inter-ring traffic switching. OC-48 SONET rings are the constituting module for the MAN.

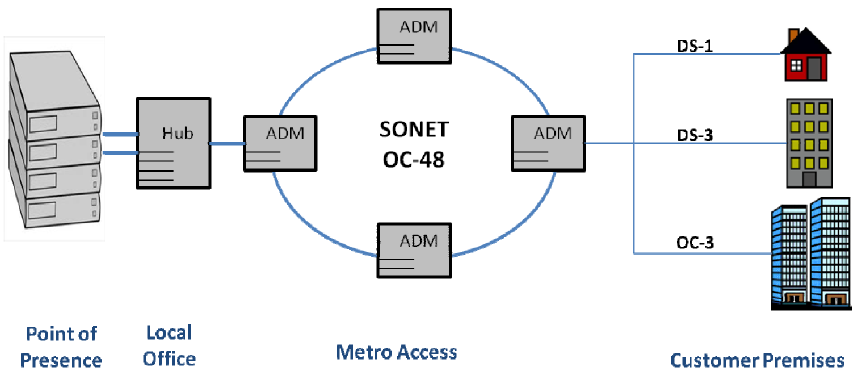

Figure 20. Typical SONET/SDH network.

Introducing RPR technology the structure does not change drastically. Let us remember the reader that RPR is a MAC layer technology, thus independent from the underlying physical layer. In contrast to the SONET scenario, connection to the end users is offered by 10/100 Ethernet and 1Gb Ethernet interfaces. The RPR network is thus depicted as in Figure 21.

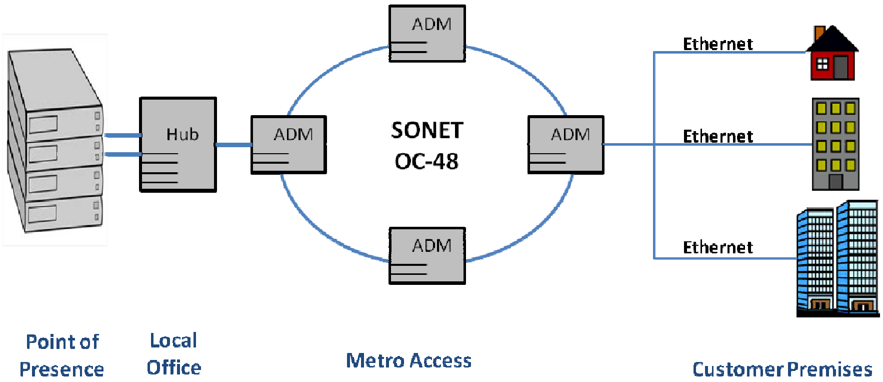

Figure 21. Typical RPR network.

Solid data about the costs for the build-out of a SONET or RPR network are hard to find. Therefore, even though it is consolidated among operators that deploying a RPR networks is less expensive if compared with SONET-based, we assume equal deploying costs for the two solutions. It allows us to assume how CapEx and Opex change as we scale the network.

The price we assume for cost comparison are enlisted in Table 4 [65].

Service	Price/month
Full T1	$ 1,000
Fractional T3 (6 Mbit/s)	$ 2,600
Full T3	$ 25,000
OC-3	$ 50,000
OC-48	$ 450,000
10/100 Mbit/s Ethernet	$ 1,000
1Gbit/s Ethernet	$ 10,000

Table 4. Service pricing figures

For the baseline scenario, we can assume the MAN made up of five nodes, each serving twenty subscribers with a 1.5 Mbit/s connection. How the two networks provide the required bandwidth is summarized in Table 5.

	SONET/SDH only	RPR
Numbers of nodes (SONET/SDH or RPR ADMs)	5	5
Subscribers per node	20	20
Total subscribers	100	100
Bandwidth per subscriber	1.5 Mb/s	1.5 Mb/s
Bandwidth required per node	20* 1.5 Mbit/s=30 Mb/s	20* 1.5 Mbot/s=30 Mbit/s
Total bandwidth required	5* 30 Mbit/s=150 Mb/s	5* 30 Mbit/s=150 Mbit/s
Access ring speed	OC-48 (2.5 Gbit/s)	OC-48 (2.5 Gbit/s)
Effective ring bandwidth	2.5 Gbit/s	2.5 Gbit/s
Port count	100 T1 ports	100/10 Ethernet ports
Per port cost/month	$ 1,000	$ 1,000
Number of access rings required	1	1

Table 5. Baseline scenario: SONET/SDH only vs RPR.

The end users do not see difference in prices. The two solutions are equivalent. It is in fact a real-like assumption the two different solutions co-existing over the same network.

2.8.2 Small increment in the per-user bandwidth

Let assume to increase the bandwidth offered to each end user from 1.5 to 5 Mbit/s. The number of users does not vary.

Whilst the 10/100 Ethernet interfaces of the RPR can accommodate the increased bandwidth, TDM-based T1 interfaces have to upgraded to fractional T3s (6 Mbit/s). This involves also the T1 circuits tear-downs and the fractional T3s provisioning from the customer premises to each ADM on the network by the service providers. Hence CapEx (hardware costs of T3s) and OpEx (truck rolls and circuit tear-down/provisioning) comes along with the upgrade in the SONET network. No increase in the number of OC-48 access rings is required. The two solutions for the new scenario are summarized in Table 6.

	SONET/SDH only	RPR
Numbers of nodes (SONET/SDH or RPR ADMs)	5	5
Subscribers per node	20	20
Total subscribers	100	100
Bandwidth per subscriber	6 Mbit/s (fractional T3)	5 Mbit/s
Bandwidth required per node	20* 6 Mbit/s=120 Mbit/s	20* 5 Mbit/s=100 Mbit/s
Total bandwidth required	5* 120 Mbit/s=600 Mbit/s	5* 100 Mbit/s=500 Mbit/s
Access ring speed	OC-48 (2.5 Gbit/s)	OC-48 (2.5 Gbit/s)
Effective ring bandwidth	2.5 Gbit/s	5.0 Gbit/s
Port count	100 fractional T3 ports	100 10/100 Ethernet ports
Per port cost/month	$ 2,600	$ 1,000
Number of access rings required	1	1

Table 6. Scenario with small increment in the per-user bandwidth: SONET/SDH only vs RPR

2.8.3 Rapid increment of the per-user bandwidth

We now assume a more rapid increase of the per-user required bandwidth: 80 users upgrade their service from 5 to 40 Mbit/s, 10 subscribers to 100 Mbit/s and the rest to 1Gbit/s.

Important both capital and operational expenses are involved in the upgrade for the SONET network. TDM-mapped cards have to be replaced: Full T3 cards (44 Mbit/s) have to be installed in order to serve clients requiring 40 Mbit/s, OC-3 (150 Mbit/s) for clients requiring 100 Mbit/s and finally OC-48 (2.4 Gbit/s) for 1 Gbit/s clients. This also requires a complete new setup of channels from the customer premises to the hub, as well as truck rolls and technician to substitute the cards. If we consider the RPR scenario instead, only substitution of the 10/100 Ethernet cards with 1 Gbit/s Ethernet cards is required. Truck rolls and technicians are thus also required, but in a lower number.

What highly affects the increase in CapEx for the SONET network is the inefficient usage of the available bandwidth. As we can observe in Table 7, oversubscription is exploited in the RPR scenario; an oversubscription rate of 1:3 is assumed. The oversubscription concept is based on statistical multiplexing, which is allowed into the packet-based RPR technology but is not conceived in circuit-switching SONET. In addition to this, RPR can exploit the protection bandwidth which has to be left unutilized into the 1:1 SONET protection scheme.

The two factors together lead to a number of OC-48 access rings required for the RPR network equal to 3, compared to the 13 required for SONET.

	SONET/SDH only	**RPR**
Numbers of nodes (SONET/SDH or RPR ADMs)	5	5
Subscribers per node	20	20
Total subscribers	100	100
Each node composition:		
# of 40 Mbit/s subscribers	16	16
# of 100 Mbit/s subscribers	2	2
# of 1 Gbit/s subscribers	2	2
Bandwidth required per node	16*45 Mbit/s + 2*155 Mbit/s + 2*2.5 Gbit/s = 6.03 Gbit/s	16*40 Mbit/s + 2*100 Mbit/s + 2*1 Gbit/s = 2.84 Gbit/s**Error! Digit expected.**
Total bandwidth required	5*6.03 Gbit/s = 30.15 Gbit/s	5*2.84 Gbit/s = 14.2 Gbit/s
Oversubscription	"1:1"	"1:3"
Access ring speed	OC-48 (2.5 Gbit/s)	OC-48 (2.5 Gbit/s)
Effective ring bandwidth	2.5 Gbit/s	5 Gbit/s
Port count	80 T3 ports 10 OC3 ports 10 OC48 ports	90 10/100 Ethernet ports 10 1G Ethernet ports
Per port cost/month	T3: $25,000 OC3: $50,000 OC-48: $450,000	10/100: $1,000 1 GE: $10,000
Number of access rings required	30.15 Gbit/s / 2.5 Gbit/s = 13	142 Gbit/s / (3*5 Gbit/s) = 10

Table 7. Rapid increment of the bandwidth per user: SONET/SDH only vs RPR

2.8.4 Tenfold increase of the number of users

As the network evolves, new nodes are likely to be inserted into its architecture. We hereafter suppose to increase the number of nodes by ten times, while keeping the same bandwidth requirement mix (80% at 40 Mbit/s, 10% at 100

Mbit/s, 10% at 1 Gbit/s services). By avoiding bandwidth waste due to SONET protection scheme and by statistical multiplexing, RPR network requires about 90% less of OC-48 access rings (from 122 to 10). CapEx and OpEx increases can then be considered relatively lower. The new scenario is summarized in Table 8.

	SONET/SDH only	RPR
Numbers of nodes (SONET/SDH or RPR ADMs)	50	50
Subscribers per node	20	20
Total subscribers	1,000	1,000
Each node composition:		
# of 40 Mbit/s subscribers	16	16
# of 100 Mbit/s subscribers	2	2
# of 1 Gbit/s subscribers	2	2
Bandwidth required per node	16*45 Mbit/s + 2*155 Mbit/s + 2*2.5 Gbit/s = 6.03 Gbit/s	16*40 Mbit/s + 2*100 Mbit/s + 2*1 Gbit/s = 2.84 Gbit/s**Error! Digit expected.**
Total bandwidth required	50*6.03 Gbit/s = 301.5 Gbit/s	50*2.84 Gbit/s = 142 Gbit/s
Oversubscription	"1:1"	"1:3"
Access ring speed	OC-48 (2.5 Gbit/s)	OC-48 (2.5 Gbit/s)
Effective ring bandwidth	2.5 Gbit/s	5 Gbit/s
Port count	800 T3 ports 100 OC3 ports 100 OC48 ports	900 10/100 Ethernet ports 100 1G Ethernet ports
Per port cost/month	T3: $25,000 OC3: $50,000 OC-48: $450,000	10/100: $1,000 1 GE: $10,000
Number of access rings required	301.5 Gbit/s / 2.5 Gbit/s = 121	142 Gbit/s / (3*5 Gbit/s) = 10

Table 8. Tenfold increase of the number of users: SONET/SDH only vs RPR

2.8.5 Introduction of Next-Generation SONET and Metro Ethernet

As we mentioned in Paragraph 3.3, in order to drop the costs of SONET/SDH bandwidth increase, some solutions aiming to reduce SONET drawback in highly asymmetric packet-switching environment have been proposed. Thanks to Virtual Concatenation (VCAT) it is possible to concatenate efficiently traffic to be transported over SONET, thus providing a finer granularity which leads to bandwidth savings.

For instance, 100 Mbit/s Ethernet can be transported in two discrete STS-1s (~2·52=104 Mbit/s) rather than in an STS-3 (155 Mbit/s) as before. Similarly, 21 STS-1 concatenated together are sufficient to carry one gigabit Ethernet (one OC-48 circuit before, equivalent to 48 STS-1).

This scenario with VCAT introduction, that is deploying Ethernet native interfaces for the SONET network, is summarized in Table 9. We can observe how RPR oversubscription still makes OpEx and CapEx required for a RPR network lower if compared with SONET solution.

	SONET/SDH with VCAT	RPR
Numbers of nodes (SONET/SDH or RPR ADMs)	50	50
Subscribers per node	20	20
Total subscribers	1,000	1,000
Each node composition:		
# of 40 Mbit/s subscribers	16	16
# of 100 Mbit/s subscribers	2	2
# of 1 Gbit/s subscribers	2	2
Bandwidth required per node	16*45 Mbit/s + 2*104 Mbit/s + 2*1.092 Gbit/s = 3.112 Gbit/s	16*40 Mbit/s + 2*100 Mbit/s + 2*1 Gbit/s = 2.84 Gbit/s
Total bandwidth required	50*3.112 Gbit/s = 155.6 Gbit/s	50*2.84 Gbit/s = 142 Gbit/s
Oversubscription	"1:1"	"1:3"
Access ring speed	OC-48 (2.5 Gbit/s)	OC-48 (2.5 Gbit/s)
Effective ring bandwidth	2.5 Gbit/s	5 Gbit/s
Port count	900 10/100 Ethernet ports 100 1Gb Ethernet ports	900 10/100 Ethernet ports 100 1G Ethernet ports
Per port cost/month	10/100: $1,000 1 GE: $10,000	10/100: $1,000 1 GE: $10,000
Number of access rings required	155.6 Gbit/s / 2.5 Gbit/s = 63	142 Gbit/s / (3*5 Gbit/s) = 10

Table 9. Introduction of Next-Generation SONET: SONET/SDH with VCAT vs RPR

If we then we want to compare these results with Metro Ethernet, the difference lies into the physical layer costs. While we have considered so far a legacy SONET/SDH physical layer, it can be conceived to substitute OC-48 rings with higher-capacity OC-192 rings (~10 Gbit/s) or Carrier 10G Ethernet rings.

With regards to the costs, if comparing OC-192 with 10G Ethernet, leasing a fiber and running the latter is considered to be a tenth of the cost [66]. We can also take as a reference the data provided in [67] for installation costs of the two solutions, which explains why leasing of bandwidth over Ethernet network can be offered at a much more competitive price. It is said that deployment of a OC-48 ring (2.4 Gbit/s) comes to a cost of $ 910,000, while for about the same price a Ethernet-based ring providing as about four times the bandwidth can be installed.

Thus, with the three assumptions of (i) leasing 10G Ethernet is a tenth of the cost when compared with SONET, (ii) equal oversubscription rate 1:3, and (iii) efficient bandwidth utilization, which means SONET 1:1 protection scheme is not exploited, this ultimate scenario is summarized in Table 10.

	RPR	**Metro Ethernet**
Numbers of nodes (SONET/SDH or RPR ADMs)	50	50
Subscribers per node	20	20
Total subscribers	1,000	1,000
Each node composition:		
# of 40 Mbit/s subscribers	16	16
# of 100 Mbit/s subscribers	2	2
# of 1 Gbit/s subscribers	2	2
Bandwidth required per node	16*40 Mbit/s + 2*100 Mbit/s + 2*1 Gbit/s = 2.84 Gbit/s **Error! Digit expected.**	16*40 Mbit/s + 2*100 Mbit/s + 2*1 Gbit/s = 2.84 Gbit/s
Total bandwidth required	50*2.84 Gbit/s = 142 Gbit/s	50*2.84 Gbit/s = 142 Gbit/s
Oversubscription	"1:3"	"1:3"
Access ring speed	OC-48 (2.5 Gbit/s)	10GbE (10 Gbit/s)
Effective ring bandwidth	5 Gbit/s	10 Gbit/s
Per access ring cost/month	OC-48: $ 450,000	10 GbE: $ 180,000
Port count	900 10/100 Ethernet ports 100 1Gbit/s Ethernet ports	900 10/100 Ethernet ports 100 1G Ethernet ports
Per port cost/month	10/100: $1,000 1 GE: $10,000	10/100: $1,000 1 GE: $10,000
Number of access rings required	142 Gbit/s / (3*5 Gbit/s) = 10	142 Gbit/s / (3*10 Gbit/s) = 4

Table 10. Introduction of MEtro Ethernet: RPR vs Metro Ethernet

In the scenario above, the price differences among SONET, RPR and Optical Ethernet ADM have not been considered relevant in the analysis. In fact the three prices do not differ too gravely, as summarized in Table 11.

Device	Price	Source
SONET ADM	ca. $ 5,000	www.adtran.com
RPR ADM	ca. $ 8,000	www.adtran.com
10G Ethernet ADM	ca. $ 5,000	

Table 11. Price figures for ADMs.

3 Metro Network with Flexible Grid

In the previous Chapter the reader has been introduced to how the Metro Area Networks have evolved till present time, keeping an eye on what fundamentally drives the decisions of network operators: the economical revenues. Some experimental systems have also been presented. In this Chapter we deal with what is considered to be the very next future of optical networks, which is likely to endure also in the long-term: the vision of the optical spectrum as a continuum where the allocation of lightpaths is not constrained by rigid optical grids.

In Section 3.1 we describe the SLICE project, that has first foreseen this approach. The ITU-T Recommendation that followed, and which standardizes such flexible approach, is described in the Section 3.2. A further technique, i.e. the possibility of exploiting Multiple Modulation Formats (MMF), which is expected to remarkably improve the network performances, especially in the metro segment, is introduced in the Section 3.3. In Section 3.4 the two techniques, namely flexible grid and MMF, are combined together in order to have a single view of the further flexibility in spectrum allocation that they bring. Hence from Section 3.1 to Section 3.4 a detailed explanation of what is foreseen to be the very next future of metro networks is provided. In Section 3.5 the model of network we adopt is presented. The assumptions defining such model and its relation with the regulations are described.

3.1 A forerunner project: the SLICE concept

The underlying driving factor of the evolution for the technologies so far presented is the strain for the most efficient utilization of the deployed resources. When we move into the optical field, the possibility of sending a multitude of different signals over the same link (i.e. fiber) using lambda-multiplexing technology has been a fundamental improvement with regard to the exploitable bandwidth. The current reference standard for WDM (Wavelength Division Multiplexing) technology is the ITU-T Recommendation G.694.1, whose first version of June 2002 [68] has been recently superseded by a second revision in February 2012 [69] .

WDM systems are divided in different wavelength patterns, according to the channel spacing imposed between two adjacent wavelengths. The first version of G.694.1 specifies a grid of frequencies spaced by either 100 GHz (or equally about 0.8 nm at 1550 nm) or 50 GHz (0.4 nm) or 25 GHz (0.2 nm) or 12.5 GHz (0.1 nm). These spacings are referred to as DWDM (dense WDM) grids. The ITU-T grid that is more likely to be found in WDM networks presents a channel spacing of 50 GHz, the right tradeoff between wavelength-drift tolerance and spectrum "density of population". In the rest of the work, with DWDM we are going to refer to the 50 GHz grid only.

In this Subsection we provide a quick glance to the concept that can be considered the precursor of flexible grids: the SLICE (spectrum-sliced elastic optical path network) project [60]. It has been the first to propose a novel spectrum efficient and scalable network architecture able to provide sub-wavelength and super-wavelength traffic utilization. The wavelength granularity can then be considered as removed, or at least replaced with a minigrid whose granularity is considerably smaller than WDM (before G.694.1 regulatory, spectrum widths of 5 or 10 GHz had been suggested).

The proposed architecture is able to expand and contract the optical path, that is the width of the optical spectrum utilized from the transmitting transponder, according to the traffic volume and user request. The optical resources are sliced off in spectral intervals, that are allocated contiguously to the end-to-end all-optical path. Guardbands, which are portions of the spectrum of about the same size as spectral intervals, are needed in order to separate different optical paths. In Figure 22 it can be observed how the optical spectrum is assigned in SLICE, compared to conventional grids. In the SLICE concept, bandwidth-variable transceivers are assumed to be adopted.

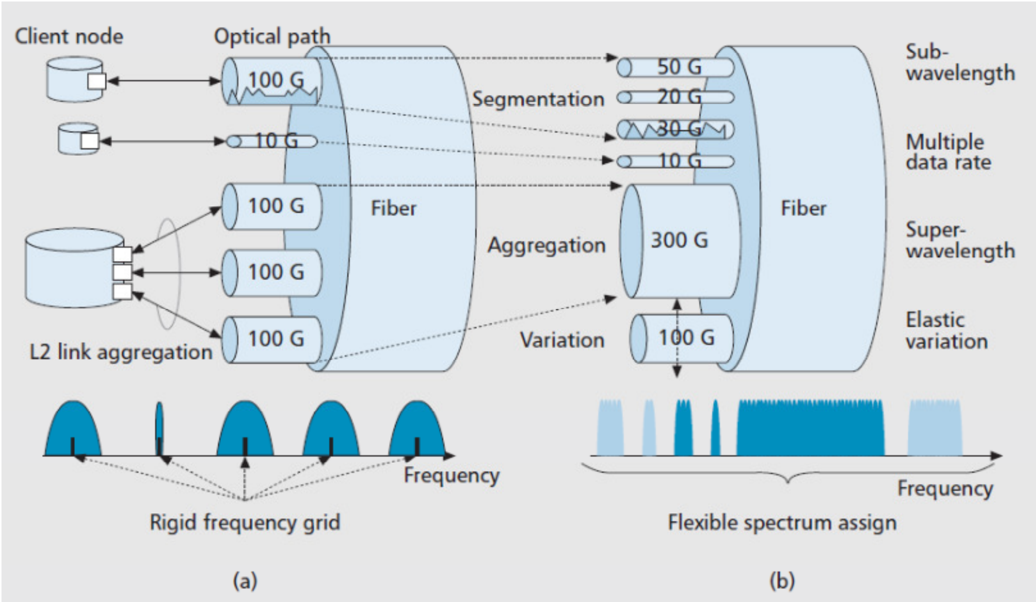

Figure 22. Spectrum assignment in (a) conventional optical path network and (b) SLICE architecture.

In Figure 22 it is shown that the unique features of the SLICE concept in terms of segmentation and aggregation of spectral resources allow for efficient accommodation of multiple data rates, as well as elastic variation of allocated resources. From the top of Figure 22, sub-wavelength allocation consists of allocating just enough optical bandwidth to accommodate the client traffic. Thus, when only a fraction of the channel is required, under-utilization of an occupied channel is avoided. Moreover, SLICE enables spectrally-efficient direct accommodation of mixed data bit rates in the optical domain because of the flexible assignment of spectrum. Finally, the SLICE concept enables the creation of a super-wavelength optical path contiguously combined in the optical path whilst, in traditional rigid frequency grid, several separated channels are required. As previously said, the SLICE project adopt bandwidth-variable transponders thus, in addition to the aforementioned features, elastic variation of the allocated spectrum is allowed.

3.2 Flexible Grid and ITU-T Recommendation G.694.1

We have said in the previous Section how WDM systems have well-defined spacing between two adjacent lambdas, and that such patterns of optical spacing are regulated by ITU-T Recommendation G.694.1. We have also hinted at the fact that a second revision has superseded its first version.

It is in this second version that the concept of flexible grid makes its first appearance into a regulatory. The rigid grids which impose a well-defined channel spacing (either 100 GHz or 50 GHz or 25 Ghz etc.) are referred to as "rigid grids". The definition of flexible DWDM grid is introduced as follows [69]:

> For the flexible DWDM grid, the allowed frequency slots have a nominal central frequency (in THz) defined by:
> 193.1 + n × 0.00625 where n is a positive or negative integer including 0 and 0.00625 is the nominal central frequency granularity in THz and a slot width defined by:
> 12.5 × m where m is a positive integer and 12.5 is the slot width granularity in GHz.
> Any combination of frequency slots is allowed as long as no two frequency slots overlap.

Two innovative features are evident to the reader:

- The term **frequency slot** goes substituting in the definition what has always been referred to as channel, i.e. the lambda.
- Compared with fixed grids, a finer granularity is allowed; frequency slots can vary their width by steps 12.5 GHz wide. A granularity of 6.25 GHz for nominal central frequency allows to place a slot having a width that is an even multiple of 12.5 GHz next to one having a width that is an odd multiple of 12.5 GHz without a gap.

A very important feature that is also implicitly intended here in this definition is the fact that no limitation in the width of the frequency slots is imposed. This means that the range of frequencies allocated to a slot is variable, a slice of spectrum as wide as it is needed, though obeying the flexible grid definition cited above.

Thereafter a fundamental role is played by the introduction of Wavelength Selective Switch (WSS). Whilst with DWDM a set of adjacent channels with the same source-destination pair were treated independently one from another, with the WSS the transceivers belonging to this set of channels allocated next to each other and carried throughout the network as a single entity, nominally the frequency slot. This allows to avoid the spectral inefficiency caused by **guardbands**. Guard bands are portion of spectrum left unused in order to prevent inter-channel interferences. We can see in Figure 23 how part of the traditional 50-GHz DWDM grid is addressed to bilateral guardbands, each 11 GHz wide [70].

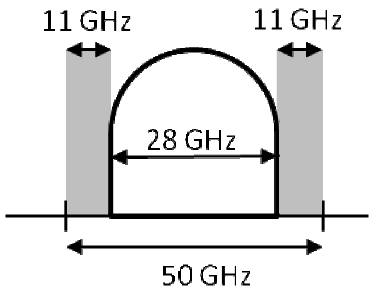

Figure 23. Spectral composition of a 50-GHz DWDM channel

Thus the actually used portion of spectrum per channel is only 28 GHz. This is due to the fact that in mesh networks it is not uncommon that 20 WSS are cascaded along the transmission lightpath; the single pass filtering shape of the WSS is thus drastically reduced because of misalignments among the cascaded filters [71]. The transmission function of a DWDM filter, after a single pass and after 20 cascaded filters, is illustrated in Figure 24. It can be observed as the 3-dB bandwidth of the filter after a single pass is approximately of 45 GHz; after 20 filter-passes, the 3-dB bandwidth is reduced to only 31 GHz.

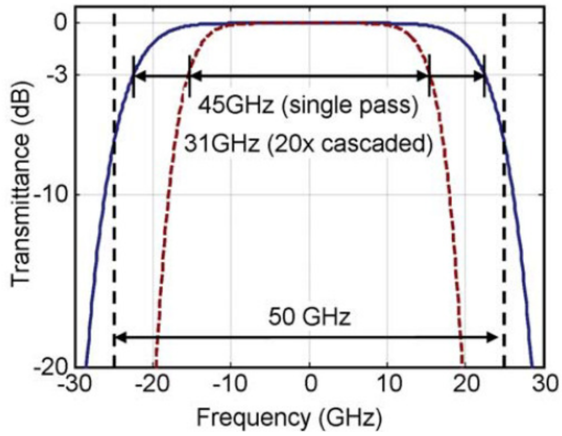

Figure 24. Transmission function of a DWDM filter, after a single pass and after 20 cascaded filters

With the introduction of bandwidth-variable frequency slots, the necessity of inter-channel guardbands becomes unnecessary. We can thus observe in Figure 25.a] how three lightpaths forming three different channels, even though having the same source-destination pair, are carried through the network in traditional fixed-grid DWDM network. In Figure 25.b] the equivalent total portion of spectrum is allocated, forming a frequency slot. But inside this portion of spectrum we can see how, considering what were before three different channels as a single entity, the spectrum utilization results much more efficient since considered as a continuum.

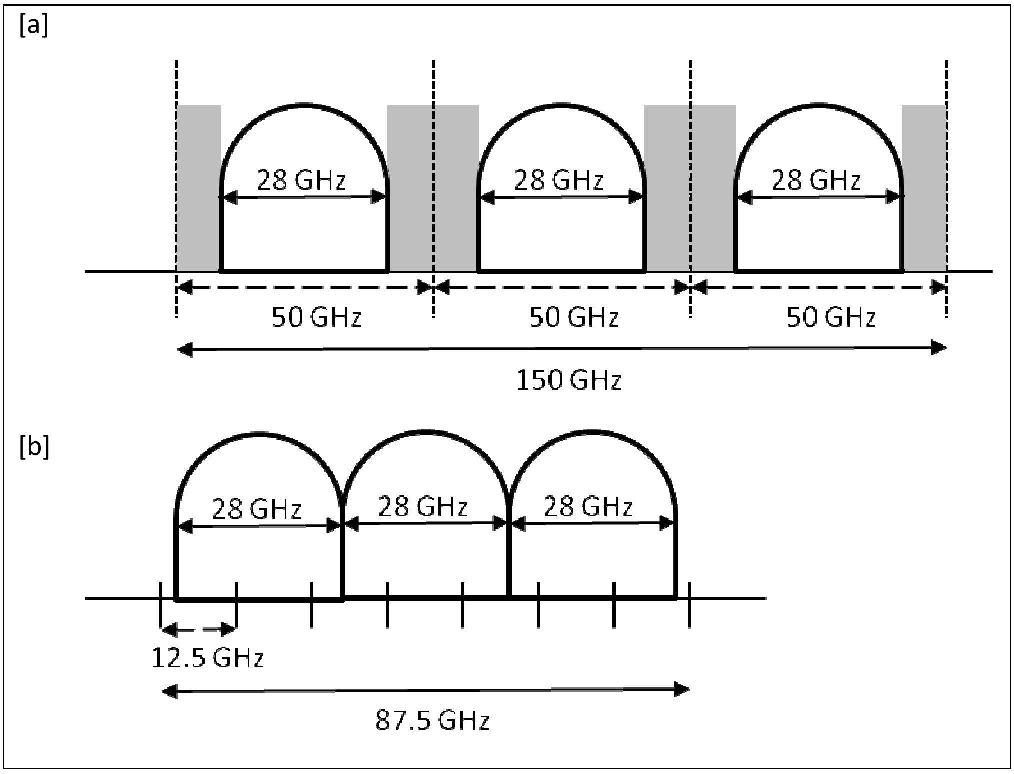

Figure 25. Three lightpaths with the same source destination pair in (a) traditional DWDM network and in (b) flexible grid network

For sake of completion, an ultimate aspect has to be pointed out. We have reported the transmission function of a typical DWDM filter. Improvements in technology have also been obtained with regard to this aspect: more recent high-definition WSS filters allow for finer filtering. These new filters are already commercially available. We simply report in Figure 26 the comparison between traditional WSS and high-definition WSS filters; for traditional WSS filter, a super-channel spacing of 50 GHz refers to traditional DWDM filters. By relative 3-dB filter bandwidth is meant the percentage of the superchannel spacing that can actually be used for traffic allocation.

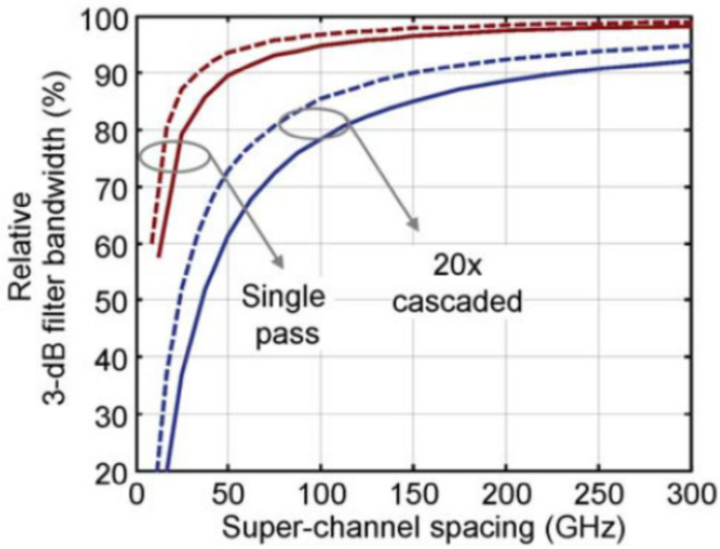

Figure 26. Relative 3-dB filter bandwidth as a function of the total bandwidth allocated to a superchannel after a single pass (red lines) or after 20 cascaded filters (blue lines). Solid lines are current WSS filters, dotted lines represent high-definition WSS filters.

3.3 Multiple Modulation Format

In addition to the attractive solution of exploiting the spectrum efficiency provided by flexible grid solution, thanks to the introduction of frequency slots, another new trend has been brought up recently. It consists of exploring the possibility of choosing the modulation format to adopt for a certain transmission.

Transmission capacity over a link has been constantly pushed upward, 100 Gbit/sec over a single wavelength has been demonstrated [61] and development programs for higher rates are already at an advanced status [62]. Having a single device able to carry such a huge amount of data is considered the leading path to follow. Two main directions to keep enhancing the information transmitted per time unity (bitrate):

- Improve the signal rate (or equivalently called baud rate)
- Improve the modulation format.

The former is defined as the symbols transmitted over the channel per time unity, while the latter determines how many bits of information are transmitted with a single symbol. As an example, we can consider FSK (Frequency-Shift Keying) and QPSK (Quadrature Phase-Shift Keying) modulation formats. In FSK, a

1 is represented by frequency f_1 while a 0 is represented by frequency f_0. One bit of information per symbol is thus transmitted, which means that a bit rate of 1000 bit/sec would correspond to a symbol rate of 1000 baud/sec. If adopting QPSK instead, the digital information is encoded using 4-level differential PSK, as in Table 12. Hence, a symbol rate of 1000 baud/sec would carry an information of 2000 bit/sec.

Digital bits	Phase shift
00	+90
01	0
10	180
11	270

Table 12, Data encoding in QPSK

As a result, high modulation formats together with highly capable electronic digital processing yields to the possibility of very high bit rates. But at such high bit rates, the signal impairments significantly limit the reach of regenerator-free optical distance. Then the upcoming question is [63]: is 100 Gbit/sec always the best solution?

It can be convenient for the network operators to transmit at a lower bit rate over a long-distant optical path, in order to avoid opto-electronic conversion and regeneration at intermediate nodes. Thanks to the recent improvements in optical transmission technologies, it has been suggested the introduction of new “elastic” transponders capable of choosing the best modulation format to be adopted for the transmission. The hint for this solution has been borrowed from wireless communication, where modulation format can be chosen according to the channel condition. A good enough simplification of channel condition for optical communication can be considered the distance of the receiver form the transmitter. In fact, in contrast to most wireless scenarios, optical channels can be assumed to be flat channels. By flat channel we here mean the fact that, while in wireless scenario the visibility of the two communicating points is a variable and, for instance, weather conditions can affect the transmission distance, this do not occur in optical channels. In optical channels the signal is confined within the conductor (i.e. the fiber) and external factors degrading the transmission efficiency can be disregarded. Thus the following formula can be assumed [64]:

- $C = \frac{C_0}{2}\left(1 + \log_2 \frac{2l_0}{l}\right) \qquad where\ l \leq 2 \cdot l_0$.

The formula expresses how the link capacity C increases based on given system performance for a certain modulation format with initial capacity C_0 and reach l_0. It is thus a realistic scenario assuming to halve the transmission distance for every increase of the modulation format by 1 bit. As an example, if we assume an optical reach l_0 for an optical link with capacity C_0 by exploiting QPSK modulation format, if we adopt 8-QAM instead as modulation format the reach is reduced to $l_0/2$. Equivalently, utilization of BPSK would increase the optical reach to $2l_0$.

3.4 Degrees of Freedom of next generation MMF elastic transponders

We have mentioned above how next generation transponders, fruit of the combination of the two analyzed techniques, will allow for a more efficient and flexible utilization of optical resources. We can easily identify two Degrees of Freedom (DoFs) that constitute a big advantage if comparing these devices with already deployed techniques:

- The modulation format (the coding rate being equal) can be chosen according to the distance between the transmitter and the receiver. Long-distance transmission can be preferred to routed with lower bit-rate but also lower number of required opto-electronic devices. In short-distance transmissions, modulation format can be pushed to higher signal constellation sizes (from DPSK to QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, …).
- The spectral width utilized to transmit the data is also a variable. Spectrum intervals, make it possible to treat optical fiber as a sharable

almost-continuous resource pool. The conventional fixed-spectrum grid is replaced with a minigrid of narrower spectral intervals; frequency slots can be allocated their width varying with a granularity of 12.5 GHz.

Both these DoF bring important enhancements in MANs.

With regards to the modulation format, it is particularly in the metro segment that the network operator can find itself dealing with very short optical link (up to few kilometers), where the possibility of higher modulation format increases drastically the spectral efficiency. In the same time, the optical metro ring can have a circumference length in the order of the hundreds of kilometers. Let assume for example a metro ring covering a metropolitan area whose radius is 50-km long, the ring length is about 300 km. MMF thus gives the possibility of setting up a low-rate (i.e. low complexity of the modulation format) optical link able to cover this order of distances as well.

Shifting the focus upon spectral width, the reader has to keep in mind the high dynamicity that the traffic figure into the metropolitan area is characterized with. In a metropolitan area, the variation in terms of required data from a certain node from day time to night time can be remarkable. Hence the possibility of allocating elastically the bandwidth only when actually required highly affects the efficiency of resource utilization

Both of the DoF embedded in the same device are an attractive solution for service providers. It is then understandable why, at present time, important research and work are being done by several protagonists of the telecommunication world in order to bring flexible MMF solution to maturity.

3.5 Metro Network Model adopted for the RSA algorithm

We are going in this Section to illustrate the model of network that has been adopted in the development of the RSA (Routing and Spectrum Assignment) and RMLSA (Routing, Modulation Level and Spectrum Assignment) algorithms contained in the subsequent Chapters 4 through 7. Assumptions with regard to various aspects of the metro network under study are necessary; in Subsection 3.5.1 network architecture nodes are dealt with, in Subsection 3.5.2 a special focus to the compatibility with the ITU-T Recommendation G.694.1 is provided, in Subsection 3.5.3 assumptions upon the composition of frequency slots are given while in Subsection 3.5.4 the attention is dragged on the multiple modulation formats. The assumptions are enlisted with **(A.x)** and highlighted in the text with bold character.

3.5.1 Network Architecture and Nodes

As said in Chapter 2, it is common to find metro networks organized as sets of interconnected rings. For the RSA and RMLSA algorithms, **(A.1) the only network architecture that will be studied will be a ring structure**. With regard to the links and the capacity of the links, **(A.2) each link is a pair of unidirectional fibers per link (one fiber per direction)**. **(A.3) Each fiber has an exploitable spectrum that is 4.4 THz wide**, hence equal to the Common Band. Even though the developed algorithms are not dependent on the number of nodes of the networks, in this work we are going to assume that **(A.4) the network is made of six nodes**. The reason behind this limitation is a simple matter of time; since a multitude of aspects is going to be explored, a higher number of nodes would require much longer simulation times. This would imply the impossibility of exploring all the diversified inputs that these two algorithms take into account. We also add the assumption that **(A.5) the number of transponders available at each node is not limited**.

3.5.2 Compatibility with G.694.1 (02/12)

Providing a numerical evaluation of the advantages brought by introduction of flexible grids is one of the main goals of this work. It is then is important to draw clearly how the model adopted for the work matches the recent ITU-T Recommendation G.694.1 introduced to the reader in Section 3.2 .

First of all, our model differs from the recommendation for the spectrum granularity exploitable by frequency slots. Whilst a granularity of 12.5 GHz for slot width is recommended in the ITU-T document, we assume that (**A.6**) **Slot width granularity is fixed at the value of 6.25 GHz.** The reason behind this discrepancy lies behind the fact that, at the beginning of this work, still no official Recommendation had been released by ITU-T. Nevertheless, rumors about the possibility of choosing between both granularities, 6.25 GHz and 12.5 GHz were circulating. With the intention to underline the advantages of flexible grid over DWDM, the 6.25 GHz granularity seemed to fit better with the traditional transceiver optical width of 28 GHz. Adopting this finer granularity, a single transceiver can be contained in a frequency slot 31.25 GHz wide. On the other hand, the choice of a granularity by steps 12.5 GHz wide would imply that a single transponder had to be contained in an frequency slot of width 37.5 GHz, leading to an important inefficiency.

3.5.3 Spectrum Slices, Transponders, Super-channels and Guardbands

We have stated in the previous Subsection that granularity of 6.25 GHz will be the reference measure for the frequency slot width. In the rest of the work, we will refer to such optical width with the term **spectrum slice**. The 4.4 THz of each fiber can then be considered as ideally formed by a set of 704 spectrum slices; the frequency slots occupying an integer number of spectrum slices; the spectrum assignment problem reduced to assign in which spectrum slice start to install the frequency slot; and so on.

Furthermore, in the definition of flexible grid we reported in Section 3.2, there is no particular reference upon how frequency slots have to be formed: "Any combination of frequency slots is allowed as long as no two frequency slots overlap". The type and the optical width of the transceiver to be used is not specified: they can also be variable-bandwidth transponders, as first assumed in the SLICE concept. In our work **(A.7) Transponders have fixed optical width equal to 28 GHz hence consequent symbol transmission rate equal to 28 Gbaud/sec.**

As a direct consequence, in order to make this assumption co-exist with the flexible grid solution, it follows the introduction of **super-channels**. Multi-carrier super-channel is a term that is already of common-use in up-to-date literature; it usually refers to optical transmission systems which exploits super-wavelengths (beyond DWDM) portions of spectrum in order to achieve channel rates greater than 100 Gbit/sec [72]. In this work with this term we refer to a set of transceivers allocated adjacently to each other in order to form a sole frequency slot. Thus a frequency slot where more than a single transponder is allocated can also be called super-channel.

Even if the flexibility introduced by the cited recommendation ITU-T G.694.1 (02/12) is constrained by this assumption, it is more realistic to assume in the first phase of the deployment of the new flexible solution the adoption and re-utilization of legacy technologies and assets, such as fixed-bandwidth transponders. We can then refer to the previously observed case [Section 3.3) where three lightpaths in traditional fixed-grid DWDM network are organized in three different channels, even though having the same source-destination pair. In Figure 27.a] we propose again their formation, while the equivalent superchannel is illustrated in Figure 27.b] .

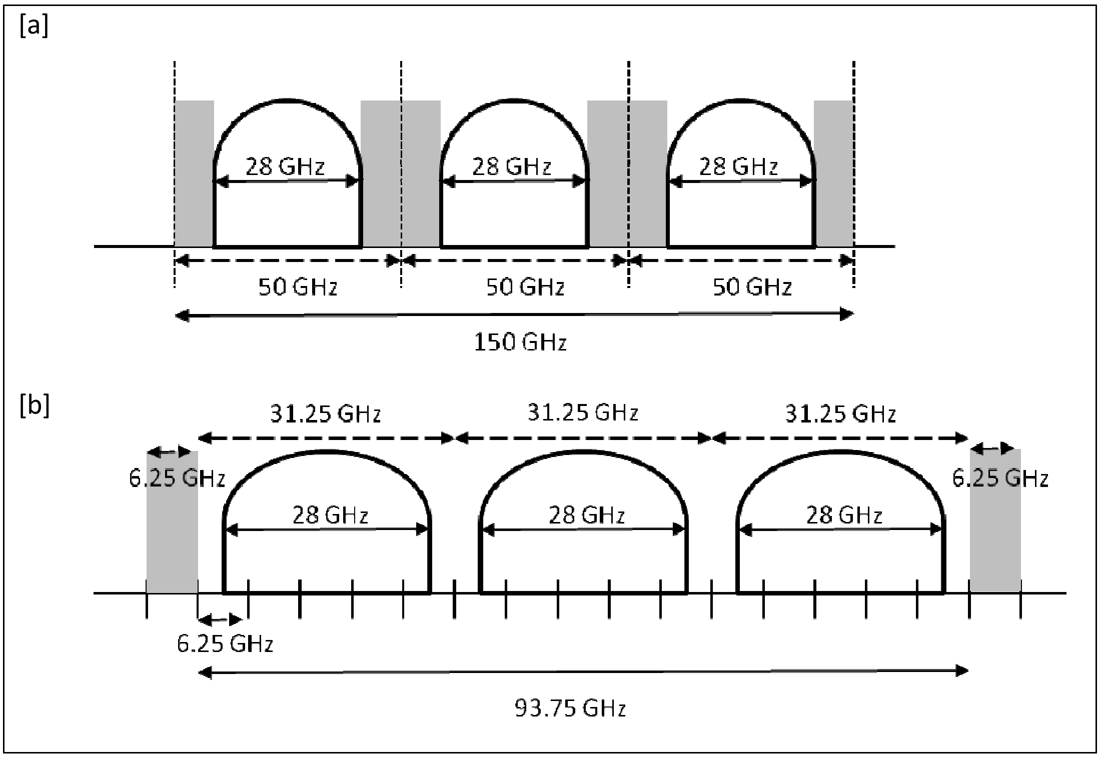

Figure 27. Three lightpaths with the same source destination pair in (a) traditional DWDM network and in (b) our model of the flexible grid network

For the sake of completion, a clarification has to be pointed out upon the representation in Figure 27.b]. The bilateral guardbands are taken into consideration, while the transponders are illustrated contiguously without sort of interruptions. When forming a superchannel, a small guardband is actually required also between adjacent transponders. In the rest of the work, these intra-superchannel guardbands are disregarded. This assumption is not as strict as it may appear, since transceivers that are considered having an optical width of 28 GHz actually work at a symbol rate of 27.75 Gbaud/sec and are inserted into five spectrum slices, thus into an optical bandwidth which is 31.25 GHz wide. A small guardband, sufficient for intra-superchannel interference, is then already implied.

Being the assumption A.7 valid, we thus introduce also the hypothesis that **(A.8) the number of transceivers that can be put one adjacent to another in order to form a superchannel in unlimited.**

In conclusion, we also have to provide a well-defined assumption with regards to guardbands. Whilst in traditional DWDM networks the concept of guardband is already included in the design of the 50-GHz spaced grid (Section 3.2), in flexible grids this element has to be explicitly introduced. Hence **(A.9) A bilateral guardband of 6.25 GHz (i.e. one spectrum slice) per side for each frequency slot is assumed. The two guardbands are always present and their widths are independent from the frequency slot width**

These bilateral guardbands will assure that the frequency slot, independently from the number of spectrum slices it is composed of, will be carried throughout the network without the quality signal decreasing due to inter-channel interference (or, more correctly, in a flexible grid we should talk about inter-frequecny slot interference).

In order to avoid confusion, let us summarize in conclusion of this Paragraph what is meant in this work with the terms spectrum slice, frequency slot and superchannel:

- **spectrum slice** is a small portion of spectrum, 6.25 GHz wide, which is the minimum granularity both for spectrum allocation and for frequency slot width. The available spectrum can thus be imagined as a sequence of adjacent spectrum slices
- **frequency slot** is the entity that goes substituting the channels of DWDM networks. It is by all means a lightpath. It is defined at its sides by two guardbands and its width is variable, though in accordance with the minimum granularity of one spectrum slice.
- **super-channel** is a frequency slot that is made by the contiguous allocation of more than a single transponder. When the frequency slot needs to allocate a bandwidth which goes beyond the capacity of a single fixed-bandwidth transceiver, then more than one transponder are allocated in the same frequency slot and thus form a superchannel.

3.5.4 Multiple Modulation Formats

As already mentioned, the possibility of using transceivers with the added ability of choosing the modulation format according to the optical distance to be traversed is explored in this work. A rule of thumbs for relating the optical reach with the link capacity (i.e. the number of bits per symbol) has been introduced in Section 3.3: it approximately asserts that the link capacity halves when the optical capacity is doubles.

We hereafter give the reference estimations adopted in this work. A set of modulation formats is given, the maximum optical reach they can cover is provided. **(A.10) The set of possible modulation formats and the related maximum optical distances they can cover are those reported in TABLE**

The data of Table 13 are extracted from [73], only the baud rate of 28 GBaud/sec into an optical bandwidth of 31,25 GHz is taken into account, where with the term optical bandwidth we refer to Figure 28.

B [GHz]	F [GHz]	Optical reach [km]			
		8-QAM	16-QAM	32-QAM	64-QAM
28	31,25	1010	495	198	138

Table 13. Maximum transmission distance for n-QAM modulation format, n= 8, 16, 32 or 64

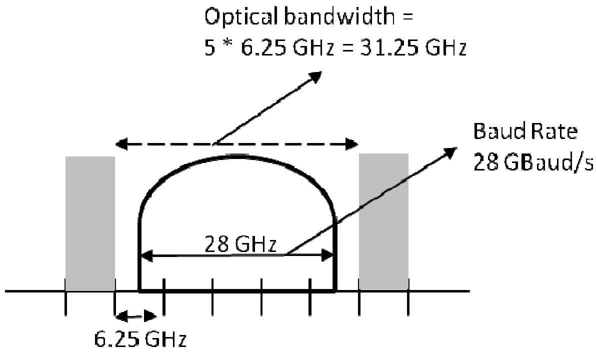

Figure 28. Spectrum assignment in our model of flexible grid network

Before introducing Multiple Modulation Format in the last part of this work, a comparison between DWDM and flexible-grid is carried out first. In this part of the analysis, the modulation format exploited by transponder is fixed. We assume that, **(A.11) when comparing transceivers with fixed modulation format into different solutions (e.g. DWDM vs flexible grid), a fixed dual-polarization quadrature phase-shift keying (DP-QPSK) constellation is assumed as unique modulation format**. This modulation technique is the most widely used for 100 Gbit/s transmission systems and, from the point of view of spectral efficiency, it is equivalent to a 16-QAM constellation matrix. It is then consistent its adoption as unique modulation format in metro networks. Adding as last assumption that **(A.12) the radius of the ring equal to 50 km**, the network had thus a circumference equal to ca. 314 km. These figures match with the maximum optical reach of 495 km for 16-QAM modulation format.

4 Routing and Spectrum Assignment (RSA) Algorithm in Metro Networks with Flexible Grid

We presented the evolution of the metro networks and what is considered to be the next step to take: the exploitation of flexible grid according to ITU-T Recommendation G.694.1, together with the already available technology of optical transceivers equipped with the Multiple Modulation Format feature. The model we adopt in order to study the performance of such innovative network has been presented in Section 3.5. The RSA problem in metro networks with flexible grid is stated as follows. Given a ring topology network consisting of six nodes connected by optical links, each with an exploitable spectrum of 4.4 THz, and dynamic traffic condition of incoming connection requests among the nodes, we aim to satisfy all the requests while minimizing the connection setup cost defined by two cost assignment weights: one taking into account the spectrum occupation, the other considering the number of utilized transponders.

Simulation runs of 10^5 connection requests generated from a Poisson process are repeated until the estimated p_{block} shows a statistical confidence of 95% and a 5% error interval.

The RSA algorithm will be explained on a step-by-step base. Each of the steps of the algorithm is not univocally defined but can be setup according to a set of policies to be provided to the algorithm as inputs. The set of policies are briefly introduced in Subsection 4.1. In the second Subsection we describe how this set of policies is combined in the flow chart describing how the algorithms processes the incoming connection requests, and their relative departures. Subsection 4.3 is focused on a central element of the algorithm, the cost matrix, which hold the setup cost calculated for each of the routing options relative to the connection request being processed. From Subsection 4.4 to Subsection 4.10 we describe each of the policies which determine the functioning of the algorithm. Finally, in Subsection 4.11, we enlist the statistics obtained as output of our simulations in order to evaluate the performance of the algorithm, also in relation with how the input policies have been set.

4.1 Set of Policies

We hereafter provide in Table 14 all the scenarios that can be considered for the algorithm implementation. On the left column we list the policies that are applied in the algorithm proceeding. On the right column, for each policy, we apply the alternatives to choose from.

Policy	Alternatives
Traffic Distribution (Requested Bandwidth Distribution)	• Uniform • Not Uniform (SubLambda Privileged)
Grooming Options	○ Grooming ○ No Grooming
Objective Function (Cost Assignments Weights)	• α: spectrum occupation • β: transponders utilization
Clockwise vs Counterclockwise Tie Resolution	○ Basic (Clockwise Privileged) ○ Least Used Link ○ Most Used Link
Spectrum Assignment	• First Fit • Random • Spread
Superchannel Grooming	○ Deterministic ○ Holing ○ Packing
Superchannel Release	• Deterministic • Holing • Packing

Table 14. Set of policies and their alternatives to provided as parameter of the RSA algorithm

With **Traffic Distribution** we mean how the bandwidth demanded by connection requests is selected. The probability of picking a certain source-destination pair is assumed to be equally distributed among all the possible source-destination pairs belonging to the network. **Grooming Option** states whether it is possible or not to groom the traffic of an incoming connection request in an already-installed lightpath. By assigning the input values to two parameters (α and β) the **Objective Function** of the algorithm is decided. A high value of α together with a low value of β imply that, as objective, we are trying to minimize the spectrum occupation. On the other hand, setting a low value of α and a high value of β stands for an objective function prone to the minimization of the utilized transponders. The input **Clockwise vs Counterclockwise Tie Resolution** is adopted when deciding between two routing options having the same cost on the two opposite directions of the ring. **Spectrum Assignment** says where to start setting up a new lightpath. The choice of where the new lightpath is allocated affects the subsequent possibility of eventually grooming a new connection over it. **Superchannel Grooming** (or **Superchannel Release**) input determines how the superchannel is formed (or is released in case of departure of a connection that had been accommodated into a superchannel) when grooming a new connection over an existing already-installed lightpath.

After this brief introduction, we now see how these inputs are combined into the flow chart of the algorithm.

4.2 Flow Chart of the Algorithm

In case of an arrival event, the flow chart of the algorithm is as in Figure 29.

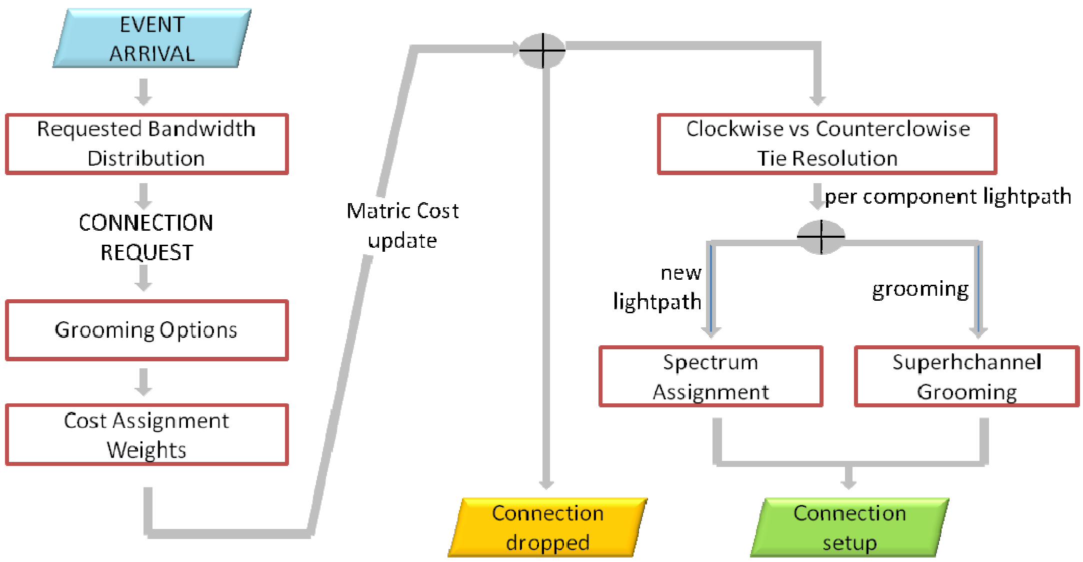

Figure 29. Flow chart of the RSA algorithm in case of arrival event

At the moment of the arrival, the probability with which the requested bandwidth of the connection is picked depends on the Traffic Distribution policy. The (s,d) source-destination pairs of the connection request are equally probable. Thus the connection request is defined. A matrix cost, containing all the possibility routing options for the picked (s,d) pair, has to be updated with the current network situation. This matrix has a number of rows equal to all the routing possibilities from s to d and takes into account both clockwise and counterclockwise direction. For each direction, all the possibilities of optical-electronic-optical conversion are taken into account. We will give the cost matrix a closer look in a following Section. The possibility of grooming the connection request over an existing lightpath is given by the Grooming Option policy, while the cost assigned to each routing option (and in particular to each **component lightpath** of each routing option) depends on the two weights of the Objective Function policy.

Once the whole cost matrix is compiled, the minimum cost routing option is chosen. If none of the routing options is viable, then the connection is dropped. Otherwise, the connection can be set up. It is possible that two routing options evolving in the two opposite directions have the same **installation cost**, that is also the minimum cost for the connection request under-process. When such situation takes place, the Clockwise vs Counterclockwise Tie Resolution policy comes into help. Once this step is done, the most convenient routing option is finally defined.

The routing option is made up of component lightpaths. Each component lightpath can be either a new lightpath to be setup or it can be an already-installed lightpath in which we groom the traffic demanded by the incoming connection request. In case of setting up a new lightpath, the Spectrum Assignment input will affect the decision of where (which optical frequency) to start installing the new lightpath within the available free portions of the interested optical spectrum. With regard to the second possibility, that is grooming over an existing lightpath, the eventual formation of the superchannel is regulated by the Superchannel Grooming input. Once this process is done for each component lightpath, the connection is setup and the resources (spectrum + transponders) are allocated.

In Figure 30, finally, it is represented the flow chart of the algorithm in case of departure event.

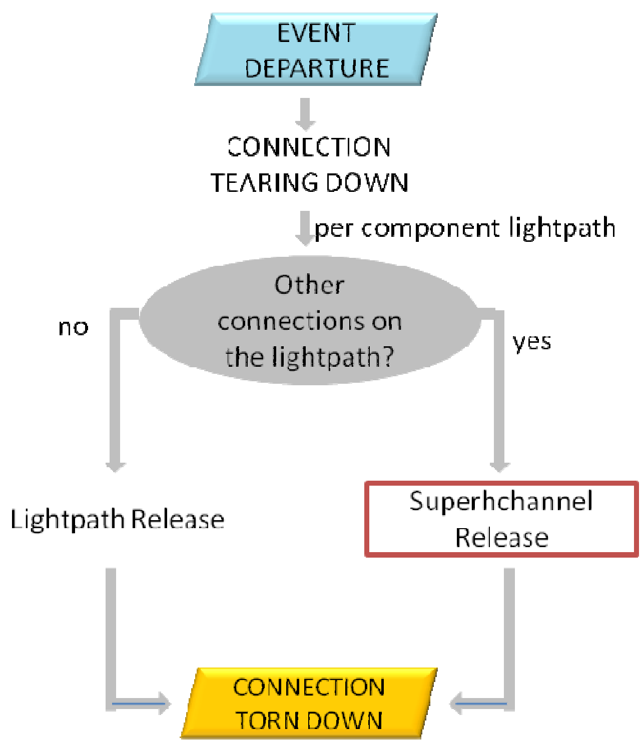

Figure 30. Flow chart of the RSA algorithm in case of departure event

The departing connection has to be torn down. For each component lightpath accommodating the connection from its source to its destination, two different situation can occur: either the departing connection is the only one accommodated over the component lightpath, or other connections are also exploiting the lightpath. In the first case, the lightpaht is released. If, on the other hand, other connections are present over the lightpath under consideration, two further cases are possible: the release of the connection does not imply any change in the allocation of the optical spectrum. This means that no transponders are released, the departure of the traffic connection will cause a transceiver to be underutilized but not uninstalled from the lightpath. Or, alternatively, with the release of the departing connection one or more transceivers belonging to the lightpath can be, in turn, released since not necessary anymore. In this case the Superchannel Release policy influences how the departing connection is extracted and the lightpath re-dimensioned. Done this process for each component lightpath accommodating the departing connection, the connection is torn down.

4.3 Cost Matrix

As seen in the previous Section, a fundamental figure in the proceedings of the algorithm is the cost matrix. In this Section we describe this structure in a more detailed way.

As already hinted, the matrix cost is a structure having a number of rows equal to all the possible routing possibilities from a certain source to a certain destination. Thus the matrix cost has a number of rows which varies according to the (s,d) source-destination pair it refers to.

Analitically:

- let (s,d) be the source-destination pair under analysis

- let N the number of nodes belonging to the ring topology network (remind that in this work only ring networks presenting 6 nodes are going to be studied)
- let L_{cw} be the number of hops in the clockwise direction
- let L_{ccw} be the number of hops in the counterclockwise direction
- we thus have:
    - $L_{cw} = mod(d - s, N)$
    - $L_{ccw} = mod(s - d, N)$

    where mod is the modulo operation, i.e. $mod(s - d, N) = (s - d)\ mod\ N$.
- and finally the total number p_{tot} of paths equals:
    - $p_{tot} = \sum_{k=1}^{L_{cw}} \binom{L_{cw}-1}{k-1} + \sum_{k=1}^{L_{ccw}} \binom{L_{ccw}-1}{k-1}$

Hence the total number of paths is made by the sum of two addends; the first addend represents the total number of clockwise paths, while the second addend the total number of counterclockwise paths. We can thus define:

- $p_{tot,cw} = \sum_{k=1}^{L_{cw}} \binom{L_{cw}-1}{k-1}$

and:

- $p_{tot,ccw} = \sum_{k=1}^{L_{ccw}} \binom{L_{ccw}-1}{k-1}$

Thus, the matrix cost for the (s,d) pair has p_{tot} number of rows. With regard to the columns, there is one column per node, hence numbered from 0 to N-1, with the addition of an extra column, the N^{th} column, which indicates whether the routing opting refers to a clockwise or a counterclockwise path. The elements of the columns 0 to N-1 are binary, while the N^{th} element can be either 1 or 2. If 1, it states that the routing option represented in the row is a clockwise option. If, on the contrary, the N^{th} element is 2, it means that particular routing option is a counterclockwise option.

For the elements in the first N-1 columns instead, we have said they are binary. A 0 says that particular node is optically bypassed (or disregarded, if not between s and d in the direction of interest in that row). On the contrary, if the value is set to 1 it means that an opto-electronic conversion takes place at the node. If the interested node is neither s nor d, then it means in that node the signal is received optically, converted into electronic and the re-inserted into the ring after a electro-optic conversion. For s and d the binary elements pointing at those two nodes are set at value 1 in each row. Obviously, in place of transmission in node s the signal is processed in electronic domain and then converted in optic. Equivalently, in place of reception in node d the signal is received optically and then converted into electronic before being processed.

The cost matrix having p_{tot} rows and N+1 columns is thus filled with binary elements by the following iterative algorithm:

(s,d) source-destination pair the cost matrix refers to;
N number of nodes;
$p_{tot,cw}$ number of paths clockwise;
$p_{tot,ccw}$ number of paths counterclockwise;
L_{cw} number of clockwise hops from s to d;
L_{ccw} number of counterclockwise hops from s to d ;
k, a, t integers;
k, a, t = NULL;

for k∈{0, … , $p_{tot,cw} - 1$ }
    if($L_{cw} > 1$)
    for a∈{1, … , $L_{cw} - 1$}
        r=round$\left(\frac{k+1}{2^a} - 0.001 - floor\left(\frac{k+1}{2^a} - 0.001\right)\right)$
        t=mod(s+a, N)
        in the k^{th} row of the matrix cost, set the value of the element in the t^{th} column to r
    end for
end for

for k∈{0, … , $p_{tot,ccw} - 1$ }
    if($L_{ccw} > 1$)
    for a∈{1, … , $L_{ccw} - 1$}
        r=round$\left(\frac{k+1}{2^a} - 0.001 - floor\left(\frac{k+1}{2^a} - 0.001\right)\right)$
        t=mod(s-a, N)
        in the $(p_{tot,cw} + k)^{th}$ row of the matrix cost, set the value of the element the t^{th} column to r
    end for
end for

for k∈{0, … , $p_{tot,cw} + p_{tot,ccw} - 1$ }
        in the k^{th} row of the matrix cost, set the values of the elements in the s^{th} and d^{th} column to 1

end for

for k∈{0, … , $p_{tot,cw} - 1$ }
    in the k^{th} row of the matrix cost, set the value of the N^{th} element to 1
end for

for k∈{$p_{tot,cw}$, … , $p_{tot,cw} + p_{tot,ccw} - 1$ }
    in the k^{th} row of the matrix cost, set the value of the N^{th} element to 2
end for

Based on the matrix cost, for each line (i.e. for each routing option) two values are calculated when a connection request arrives. The former is the cost of setting up all the component lightpaths of the routing option as new, thus without considering the possibility of grooming the request over already-installed lightpaths, if any. This will be called **no-grooming routing cost** ($c_{rout}^{no\_gr}$). The latter, on the other hand, explores possible grooming and will be named **grooming routing cost** (c_{rout}^{gr}).

In Figure 31, it is illustrated an example of matrix cost and related component lightpaths for the (s=0, d=3) pair .

Routing option	Nodes						Clockw. / Countercl.
	0	1	2	3	4	5	6
I	**1**	**0**	**0**	**1**	0	0	1
II	1	1	0	1	0	0	1
III	1	0	1	1	0	0	1
IV	1	1	1	1	0	0	1
V	1	0	0	1	0	0	2
VI	1	0	0	1	0	1	2
VII	1	0	0	1	1	0	2
VIII	1	0	0	1	1	1	2

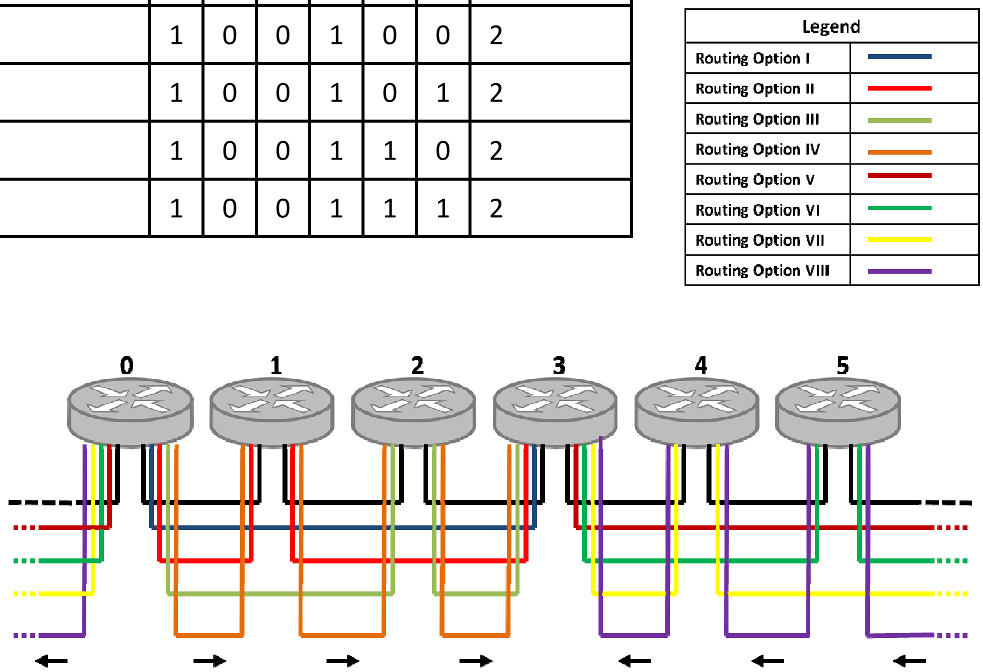

Figure 31. Example of matrix cost and related component lightpaths for the (0, 3) pair.

4.4 Traffic Distribution

Providing this policy as a input to the algorithm, the probability distribution for the required bandwidth for connection requests is set.

A maximum required bit rate by a single connection is set at 300 Gbit/s. Considering DP-QPSK modulation format, as stated in assumption A.11, such a bandwidth request will need a superchannel formed by three transceiver, or equivalently a superchannel occupying 15 spectrum slices. With only a single constellation diagram exploitable for modulating the optical signal, a univocal correlation between required bit rate and required spectrum slices is establishable. This will not be true anymore in case of MMF.

Two possible probability distributions to choose between are provided, namely **Uniform** or **Not Uniform** Traffic Distribution. The possible required electronic traffic data, the probability of each of these possibilities as well as the required optical bandwidth and the required number of spectrum slices are illustrated in Table 15 for both policies. When considering the required optical bandwidth in relation to the data traffic request, the adopted reasoning is as follows. The data traffic request is allocated in an optical bandwidth equal to the data traffic request divided by 4, since with DP-QPSK modulation formats each symbol contains four bits. The obtained results is then multiplied times 1.11; this descends from commonly used 100G Ethernet transponders, where to the 100 Gbit/s payload it is added 11 Gbit/s for Ethernet overhead and FEC, thus the final line rate being 111 Gbit/s [74]. Moreover, when more than a single transceiver is necessary, each transponder fully utilized is always allocated in five spectrum slices, i.e. 31.25 GHz. Thus, in the column “Required optical bandwidth”, when 27.75 GHz is added as first member it has to be interpreted as the occupation of five full spectrum slices, i.e. 31.25 GHz.

The Uniform Traffic Distribution, foresees a equal probability distributed between 20 Gbit/s and 300 Gbit/s, by steps of 20 Gbit/s or, considering the single modulation format, by steps of one spectrum slice. The Not Uniform Traffic Distribution has a higher cumulative probability for bandwidth requests that need one transponder at most; connection requests demanding the utilization of more than a single transponder, demand the complete utilization of the transponders (either 200 Gbit/s or 300 Gbit/s, not fractional requests)

Both distributions have equal **average required capacity** (160 Gbit/s per connection). This will allow us to compare the results obtained by varying this input to the algorithm in a more consistent way.

			Uniform Traffic Distribution	Not Uniform Traffic Distribution
Data traffic request	Required optical bandwidth	Number of required spectrum slices	Probability	Probability
20 Gbit/s	5.55 GHz	1	1/15	1/10
40 Gbit/s	11.1 GHz	2	1/15	1/10
60 Gbit/s	16.65 GHz	3	1/15	1/10
80 Gbit/s	22.2 GHz	4	1/15	1/10
100 Gbit/s	27.75 GHz	5	1/15	1/10
120 Gbit/s	27.75 + 5.55 GHz	5+1=6	1/15	
140 Gbit/s	27.75 + 11.1 GHz	5+2=7	1/15	
160 Gbit/s	27.75 + 16.65 GHz	5+3=8	1/15	
180 Gbit/s	27.75 + 22.2 GHz	5+4=9	1/15	
200 Gbit/s	2*27.75 + 27.75 GHz	5+5=10	1/15	2/10
220 Gbit/s	2*27.75 + 5.55 GHz	2*5+1=11	1/15	
240 Gbit/s	2*27.75 + 11.1 GHz	2*5+2=12	1/15	
260 Gbit/s	2*27.75 + 16.65 GHz	2*5+3=13	1/15	
280 Gbit/s	2*27.75 + 22.2 GHz	2*5+4=14	1/15	
300 Gbit/s	2*27.75 + 27.75 GHz	2*5+5=15	1/15	3/10

Table 15. Possible Data traffic requests and their probability for Uniform or Not UniformTraffic Distribution

4.5 Grooming Option

Among the set of policies to provide to the algorithm as input, it can be chosen whether exploiting grooming or not. When it is chosen not to exploit the grooming capability, the column of the cost matrix containing the no-grooming routing costs is not compiled neither considered.

It is here to be added that the choice of No Grooming as grooming parameter implies the fact that all types of grooming are prevented. In fact, we can distinguish two types of grooming: the former will be called **electronic grooming**, while to the latter we assign the name **superchannel grooming**.

Electronic grooming implies that no changes from the "optical" point of view have to be made. Let us provide an example. Consider a connection request r_a between node 0 and node 1, requiring 60 Gbit/s or equivalently 3 spectrum slices is setup over a new lightpath l_a. The capacity of the transponder of l_a is thus only partially used; l_a will be allocated occupying all the required 5 spectrum slices of its transponder t_a, but the capacity of t_a can be pushed further in order to reach its full capacity of 100 Gbit/s. For example, the remaining 40 Gbit/s can be filled with bits of padding, not carrying any information. Now assume a new connection request, r_b, incomes while l_a is still installed; r_b requiring 40 Gbit/s. It can be said that r_b is groomed electronically over l_a because it goes affecting only the transceiver t_a, which will substitute the padding bits (meaningless) with the (meaningful) traffic required by r_b. This does not imply any change into the frequency slot width, thus optically the situation id untouched.

When, on the other hand, in order to accommodate an incoming connection request an already-existing frequency slot has to be widened, then a superchannel grooming is taking place. This requires the frequency slot to have enough not-allocated adjacent spectrum slices in order to accommodate the installation of the one (or more) extra-needed transponders.

It is important to point out that, when a superchannel grooming occurs, the existing frequency slot cannot be torn down and built up again in a more convenient position inside the available spectrum, since s**ervice interruption** is not allowed.

4.6 Objective Function

The objective function the algorithm will pursue is defined by two input parameters: the **cost assignment weight for spectrum occupation** α and the **cost assignment weight for transponder utilization** β.

When compiling the cost matrix, the cost c of each component lightpath will be defined as:

$$c = \alpha * \left(\Delta_{sp} + \varepsilon(1 - \Delta_{el})\right) * N_{hops} + \beta * \Delta_{trx}$$

where:

- Δ_{sp} is the number of spectrum slices that the solution under consideration requires
- ε is an infinitesimal number. Its value can be set for instance as 10^{-4}
- Δ_{trx} is the number of further transponders required by the solution under study
- N_{hops} is the number of hops the component lightpath travels
- Δ_{el} expresses a variation form the electronic point of view. Since the incoming traffic can be expressed in integer values of spectrum slices, with a transponder occupying 5 spectrum slices, the Δ_{el} is calculated as the variation of the symbol rate transmitted by the transceiver divided by its maximum symbol rate. Two situations are possible. If the incoming request is groomed electronically over an existing frequency slot (no addition of further transponders), the Δ_{el} is thus obtained as the number of spectrum slices demanded in order to accommodate the incoming traffic divided by 5. For instance, given a frequency slot which uses one transponder and carries 40 Gbit/s, the transponder has a residual capacity of 60 Gbit/s. Such residual capacity, we assume, is filled with padding bits. Assume an incoming connection request having equal (s,d) pair requires 40 Gbit/s of traffic (or equivalently 2 spectrum slices). They can be groomed electronically over the considered frequency slot. Hence the obtained Δ_{el} is $\Delta_{el}=\frac{2}{5}$. If, on the contrary, the grooming involves the addition of further transceivers, then only the Δ_{el} over the already-installed underused transponder is calculated. Suppose the same frequency slot as before: a single transponder with 40 Gbit/s of carried traffic. Suppose the arrival of a connection request demanding 80 Gbit/s of traffic. In this case, a superchannel grooming occurs since the residual capacity of the last (in this case the only) transceiver of the already existing frequency slot is not sufficient; a further transceiver has to be

added. The Δ_{el} is then calculated over the residual capacity of the underused transceiver. The electronic data traffic it carries is increased by 60 Gbit/s, which are going to substitute the padding bits, while the remaining 20 Gbit/s are going to be accommodated over a newly installed transceiver. The Δ_{el} is hence here obtained as $\Delta_{el}=\frac{3}{5}$. The reason behind the Δ_{el} is, on one hand, to avoid that electric grooming will result for a null cost and, on the other hand, when two existing frequency slots are both able to accommodate the grooming for an incoming request, the one which will leave the higher residual capacity in the last transceiver of the resulting superchannel is preferred.

The total cost C of a routing option will be given by the sum of the costs of its component lightpaths.

$$C = \sum_i c_i$$

4.7 Clockwise vs Counterclockwise Tie Resolution

The setting of this policy intervenes when two routing options having the same cost on the two opposite directions of the ring occur. Three options are available for this parameter: **Basic**, **Least Used Link** and **Most Used Link**.

This policy determines how the matrix cost is explored after it has been compiled with the costs of all the routing options. In case more options present the same minimum cost, the routing solution has to be chosen among them. So, the Clockwise vs Counterclockwise Tie Resolution policy is used.

Basic is the easiest resolution method here presented. When a tie occurs, that is, when exploring the cost matrix, a routing option presents a cost which is equal to the momentarily stored best cost, the Basic Tie Resolution option ignores the new cost, even if equal to the at-the-moment minimum cost. It means that only one cost is stored as best cost while exploring the cost matrix and this cost is replaced only when an improving (i.e. lower) cost is found. The algorithm proceeds as follows:

Input:

- cost matrix, in the form of the array *matrix*
- p_{tot} *total* number of routing options for the pair (*s*, *d*) belonging to connection request $r_{s,d}$

Output:

- index of the routing option presenting the lowest cost.

Variables:

- *min_cost* = *UNREACHABLE* ;
- *ret_index* = 0 ;
- *tot_possibilities* = 0 ;
- *i* = 0 ;

Algorithm:

- assign *tot_possibilities* the value 2 · p_{tot}
- **for** i ϵ {0, … ,*tot_possibilities* - 1}
    - if (*matrix*[*i*] < *min_cost*)
        - assing *min_cost* the value *matrix*[*i*];
        - assign *ret_index* the value *i* ;
- **end for**
- **if** (*min_cost* != *UNREACHABLE*), which means it has been updated at least once
    - **return** *ret_index* ;
- **return** -1, which is invalid index ;

By ignoring the routing options which do not improve the temporary stored best cost, the Basic Tie Resolution option implicitly favourites the clockwise direction since, in the way the cost matrix is built, its routing options come first.

Differently from the Basic Tie Resolution option, the other two possible option the Clockwise vs Counterclockwise Tie Resolution policy can be set to allow for multiple values to be stored as temporary best cost. Thus the exploration of the whole cost matrix can return an invalid index, which means that the connection request cannot be satisfied, or a single index, which means a single routing option has the lowest cost, or an array of indexes, which means more than a single routing option present a cost equal to the lowest cost. Least Used Link and Most Used Link options allow to choose between routing options crossing the network in the two opposite directions. For the choice among routing option having the same travelling direction instead, these two options do not come into help and simply the one being first in the matrix cost is preferred.

Least Used Link option selects the routing option that has its most used link carrying the lowest load of traffic. For each of the two directions then the most used link is identified and the minimum of the two maximums is picked. Most Used Link option, on the contrary, selects the most used link carrying the highest load. Thus for each direction the most used link is identified and the maximum of the two maximums is picked.

To summarize, the Least Used Link and Most Used Link tie resolution policies follow the common algorithm below for matrix exploration, where in lines 16-17 the correct function is selected according to the option the tie resolution policy has been set to.

Input:

- cost matrix, in the form of the array *matrix*
- p_{tot} number of routing options for the pair (*s*, *d*) belonging to connection request $r_{s,d}$

Output:

- index of the routing possibility presenting the lowest cost.

Variables:

- *min_cost* = *UNREACHABLE* ;
- *ret_index* = 0 ;
- *tot_possibilities* = 0 ;
- *i* = 0 ;
- vector *index_vector*;

Algorithm:

1: – assign *tot_possibilities* the value $2 \cdot p_{tot}$

– **for** *i* ∈ {0, ,… , *tot_possibilities* - 1}

- **if** (*matrix*[*i*] < *min_cost*)
    - clear *index_vector* ;
    - assign *min_cost* the value *matrix*[*i*] ;
    - add *i* to *index_vector* ;
- **else if** (*matrix*[*i*] = *min_cost*) **and** (*min_cost* != *UNREACHABLE*))
    - add *i* to *index_vector* ;

– **end for**
– if (*min_cost* = *UNREACHABLE*)
  - **return** -1, which is invalid index ;

– else if (size(*index_vector*) = 1)
  - assign *ret_index* the only value stored in *index_vector* ;
  - **return** *ret_index* **;**

– else
  - **either** assign *ret_index* the value indexLeastUsed(*index_vector*, *s*, *d*);
  - **or** assign *ret_index* the value indexMostUsed(*index_vector*, *s*, *d*);

– **return** *ret_index* **;**

The function indexLeastUsed(*index_vector*, *s*, *d*) is defined as follows.

Variables:

– *index_iterator* = 0 ;
– *ss_utilized_on_link* = 0 , where ss stands for spectrum slices;
– *min_ss_utilized = S,* where *S* is the number of spectrum slices per fiber*;*
– *dir* = 0 ;
– *return_index* = 0 ;

Body of the function:

– **for** *index_iterator* ϵ *index_vector*
  - assign *dir* the direction the routing possibility points *index_iterator* at
  - go through all the fiber between s and d in direction dir.

For each fiber:
- assign *ss_utilized_on_link* the value equal the number of spectrum slices already allocated on that fiber
- **if** (*ss_utilized_on_link* < *min_ss_utilized*)
  - » assign *min_ss_utilized* the value *ss_utilized_on_link* ;
  - » assign *return_index* the value *index_iterator* ;
- **end for**
- **return** *return_index* ;

On the other hand, the function indexMostUsed(*index_vector*, *s*, *d*) is defined as follows.

Variables:
- *index_iterator* = 0 ;
- *ss_utilized_on_link* = 0 , where ss stands for spectrum slices;
- *max_ss_utilized = 0;*
- *dir* = 0 ;
- *return_index* = 0 ;

Body of the function:
- **for** *index_iterator* ϵ *index_vector*
  - • assign *dir* the direction the routing possibility points *index_iterator* at
  - • go through all the fiber between s and d in direction dir. For each fiber:
    - assign *ss_utilized_on_link* the value equal the number of spectrum slices already allocated on that fiber
    - **if** (*ss_utilized_on_link* > *max_ss_utilized*)
      - » assign *max_ss_utilized* the value *ss_utilized_on_link* ;
      - » assign *return_index* the value

index_iterator ;
- **end for**
- **return** *return_index* ;

4.8 Spectrum Assignment

The Spectrum Assignment policy sets in which portion of available spectrum a new (component) lightpath is to be installed.

An attempt of installing a new lightpath $l_{s,d}$ requiring n spectrum slices between node *s* and node *d* in direction *dir* in order to accommodate the connection request $r_{s,d}$ is being carried out. A spectrum slice is to be considered allocated if it is allocated in any of the links from *s* to *d* in direction *dir*. The whole spectrum is swept and an array a_{cand} of candidate spectrum slices where to start setting up $l_{s,d}$ is built. A spectrum slice indexed with x_{ss} is inserted in a_{cand} as candidate if spectrum slices x_{ss} to (x_{ss}+*n*-1) are free, and spectrum slices indexed with (x_{ss}-1) and (x_{ss}+*n*) are free or at most utilized as guardbands in the analyzed links.

Given the array a_{cand} of candidate spectrum slices, the three different options operate with different aims. **Random Spectrum Assignment** option choose randomly where to start setting up the lightpath among the elements of a_{cand}. Its functioning is shown in the algorithm below.

Input:
- array a_{cand} of candidate spectrum slices where to start setting up the lightpath

Output:
- index *first_ss* of the spectrum slice to assign as left guardband of the new lightpath

Algorithm:

1: – assign *first_ss* the value mod(random(), size(a_{cand}))
- **return** *first_ss* ;

First Fit Spectrum Assignment instead takes the first available candidate ignoring the others. The algorithm is reported below.

Input:

- array a_{cand} of candidate spectrum slices where to start setting up the lightpath

Output:

- index *first_ss* of the frequency spectrum slice to assign as left guardband of the new lightpath

Algorithm:

1: – assign *first_ss* the the first value of array a_{cand};
- **return** *first_ss* ;

Finally, Spread Spectrum Assignment goes searching for the longest sequence of adjacent candidate spectrum slices (i.e. the widest "free hole" in the optical spectrum of the interested links) and place the new lightpath in the middle of it. Its functioning as follows.

Input:

- array a_{cand} of candidate spectrum slices where to start setting up the lightpath

Output:

- index *first_ss* of the spectrum slice to assign as left guardband of the new lightpath

Variables:

- *temp_counter* = 0 ;
- *max_counter* = 0 ;
- *temp_first_ss* = 0 ;
- *first_ss* = 0 ;
- *i* = 0 ;

Algorithm:

1: – initialize both *temp_first_ss* and *first_ss* with the first value of the array a_{cand} ;
- **for** *i* ∈ {1, … , size(a_{cand})}

- **if** the difference between the value of a_{cand} in position i and the value of a_{cand} in position (i-1) is equal to 1
  - Increase the value of *temp_counter* by 1 ;
  - if (*temp_counter* > *max_counter*)
    - » assign *max_counter* the value of *temp_counter* ;
    - » assign *first_ss* the value of *temp_first_ss* ;
- **else**
  - reset the value of *temp_counter* to the value 0 ;
  - assign *temp_first_ss* the value of the i-th element of array a_{cand} ;

– end for

– assign *first_ss* the value ((*first_ss* + *max_counter*) / 2) ;

– return *first_ss* ;

4.9 Superchannel Grooming

The setting of this policy influences how, when superchannel grooming occurs, the addition of the further transponders takes place. This means that, given the number of transponders that have to be added, this policy states how many of such transponders are to be added on the “left side” and how many on the “right side”. Intuitively, with left side we mean the adjacent part of the spectrum with lower optical frequencies, or equivalently the adjacent spectrum slices characterized by lower indexes, while right side points at the higher optical frequencies adjacent part of the spectrum. The Superchannel Grooming policy aims to fragment efficiently the optical spectrum of the links, in order to provide higher possibility for future connection requests to be groomed over already-existing frequency slots or accommodated over new lightpaths.

Three possible options can be chosen for Superchannel Grooming policy: **Deterministic**, **Holing** or **Packing**. Deterministic Superchannel Grooming disregards the actual situation of the portion of spectrum adjacent to the frequency slot; a hierarchy of possible configurations for the new transponders to be installed is set a priori. The algorithm follows this hierarchy of attempts, the first applicable configuration is chosen. Differently from Deterministic instead, Holing and Packing Superchannel Grooming options take into account an analysis of the two adjacent portions of spectrum. The Holing Option aims at having the "holes" in the spectrum fairly dimensioned: if the frequency slot have a number $cntr_{left}$ of consecutive free spectrum slices on its left and a number $cntr_{right}$ of consecutive free spectrum slices on its right, this option tries to level up the two portions by favoring the addition of transponders on the side having a "bigger hole", i.e. presenting a higher number of consecutive free spectrum slices. On the contrary, the Packing Option, when to choose where to locate the further transceivers, favorites the smaller hole in the spectrum. Which is, still referring to $cntr_{left}$ and $cntr_{right}$ mentioned above, the lower number of consecutive free spectrum slices will be tried to be filled first. In this way, it is attempted to leave the "big hole" untouched. The principles behind these last two options, with regard to the possibility of future further superchannel grooming in the two adjacent portions of spectrum, are the following (we hereafter call fs_{left} the frequency slot in the left side after the set of $cntr_{left}$ free spectrum slices, while fs_{right} the frequency slot in the right side after the set of $cntr_{right}$ free spectrum slices):

- with the Superchannel Grooming policy set at the Holing option, the goal is to give fs_{left} and fs_{right} equal chances to be able to accommodate a future connection request by grooming it over themselves. It thus give a certain fairness between the two frequency slots. On the other hands, it lowers down the possibility for a connection request asking for a high number of spectrum slices of being accommodated when the free portion of spectrums are scarce. If the network is highly loaded it is likely that both $cntr_{left}$ and $cntr_{right}$ are low numbers; an incoming connection, which might exploit fs_{left} or fs_{right} and is requiring a high number of spectrum slices, might not be able to find enough space to be groomed over fs_{left} or fs_{right}. A new frequency slot might be required to be setup, leading then to spectrum inefficiency because of new guardbands, or the connection might even be dropped, if not enough free resources are available.

- The Holing Superchannel Grooming option acts instead in the opposite direction; it favorites the adjacent frequency slot which is already in a better position, from the point of view of possibility of hosting a future superchannel grooming. Between fs_{left} and fs_{right} it is identified the closer one, that is it is pointed out which is the smaller between $cntr_{left}$ and $cntr_{right}$. The allocation of the new transceivers will take place towards such direction. As a result, the frequency slot having the smaller "hole" in the spectrum between itself and the frequency slot we are considering for superchannel grooming will see such hole reduced, and will thus be less likely to host superchannel grooming for future incoming connection requests. In the other hand, the farther frequency slot will keep its privileged position and its probability of hosting superchannel grooming for future connections will be unvaried.

The functioning of these three Superchannel Grooming policies is based, in their algorithms, on five flags, or Boolean values, that are updated together with the cost matrix for the frequency slot where the superchannel grooming is taking place. The five flags are: b_l, b_r, b_{l_r}, $b_{l\_l\_r}$ and $b_{l\_r\_r}$. The information they carry depends on the number of further transceivers which need to be added, but in general terms:

- b_l and b_r states that is possible to install all the required transponders either on the left or the right side;
- b_{l_r} indicates that it is possible to install as many transponders on the left side as many on the right side;
- $b_{l\_l\_r}$ and $b_{l\_r\_r}$ are meaningful only when the connection requires the installation of three further transponders to the frequency slot of interest in order to carry the requested traffic. The former means it is possible to install two transceiver on the left side and one on the right side, the latter

states the possibility of adding one transponder on the left side and two on the right side.

It is clear how the setting of the values of these flags to either true or false is deduced from the values $cntr_{left}$ and $cntr_{right}$ introduced before. The three algorithms will return each the configuration of how to install the required further transponders. The number of transceivers that is to be added in order to form the resulting superchannel is expressed through the value Δ_{trx}.

We can now give a closer look to the three algorithms, starting from the Deterministic Superchannel Grooming reported here below.

Input

- lightpath *curr_lp* . Let us remember that *curr_lp* stores its possibilities to groom the incoming connection request on top of itself through the Booleans $b_{electronicOnly}$, b_l, b_r, b_{l_r}, $b_{l\_l\_r}$ and $b_{l\_r\_r}$
- number of transponders to be added Δ_{trx}. Possible values of Δ_{trx} are $\Delta_{trx} \epsilon \{1, 2, 3\}$;

Output

- configuration of the new transponders: where they have to be added. Possible values: LEFTONE, RIGHTONE, LEFTONE_RIGHTONE, LEFTTWO, … and so on

Algorithm

- **go to** the next step according to the value of Δ_{trx};
- **case** $\Delta_{trx} = 1$:
  - **if** b_l **then return** LEFTONE;
  - **else if** b_r **then return** RIGHTONE;
- **case** $\Delta_{trx} = 2$:
  - **if** b_{l_r} **then return** LEFTONE_RIGHTONE;
  - **else if** b_l **then return** LEFTTWO;
  - **else if** b_r **then return** RIGHTTWO;
- **case** $\Delta_{trx} = 3$:
  - **if** $b_{l\_l\_r}$ **then return** LEFTTWO_RIGHTONE;
  - **else if** $b_{l\_r\_r}$ **then return** LEFTONE_RIGHTTWO;

- **else if** b_l**then return** LEFTTHREE;
- **else if** b_r**then return** RIGHTTHREE;

It can be seen that, with the Superchannel Grooming policy set as Deterministic, simply a hierarchy between the flags of interest is established a priori.

The Holing Superhcannel Grooming option algorithm, instead, is defined as follows.

Input

- lightpath *curr_lp* . Let us remember that *curr_lp* stores its possibilities to groom the incoming connection request on top of itself through the Booleans $b_{electronicOnly}$, b_l, b_r, b_{l_r}, $b_{l\_l\_r}$ and $b_{l\_r\_r}$
- number of transponders to be added Δ_{trx}. Possible values of Δ_{trx} are $\Delta_{trx} \epsilon \{1, 2, 3\}$;

Output

- configuration of the new transponders: where they have to be added. Possible values: LEFTONE, RIGHTONE, LEFTONE_RIGHTONE, LEFTTWO, … and so on

Variables

- $cntr_{left}$= 0 ;
- $cntr_{right}$= 0 ;
- trx_{left}= 0 ;
- trx_{right}= 0 ;
- j = 0 ;

Algorithm

- count the number of spectrum slices at the left of *curr_lp* that are not allocated and can accommodate eventual additional transponders. A spectrum slice is to be considered allocated if it is allocated in any of the fibers belonging to *curr_lp* . Assign this value to $cntr_{left}$;
- count the number of spectrum slices at the right of *curr_lp* that are not allocated and can accommodate eventual additional transponders. Assign this value to $cntr_{right}$;

- from the value of $cntr_{left}$, derivate the number of transponders that can actually be installed upon such number of spectrum slices. Assign this value to trx_{left};
- from the value of $cntr_{right}$, derivate the number of transponders that can actually be installed upon such number of spectrum slices. Assign this value to trx_{right};
- **go to** the next step according to the value of Δ_{trx};
- **case** $\Delta_{trx}= 1$:
  - **if** ((trx_{left}> trx_{right}) **and** b_l) **then return** LEFTONE ;
  - **else if** ((trx_{right} > trx_{left}) **and** b_r) **then return** RIGHTONE;
  - **else**
    - assign j the value *mod*(*random*(), 2);
    - **if** ((j =0) **and** b_l) **then return** LEFTONE;
    - **else if** ((j=1) **and** b_r) **then return** RIGHTONE;
    - **if** nothing is returned, **repeat** the three steps above till a value is returned
- **case** $\Delta_{trx}= 2$:
  - **if** ((trx_{left}> trx_{right}) **and** b_l) **then return** LEFTTWO ;
  - **else if** ((trx_{right}> trx_{left}) **and** b_r) **then return** RIGHTTWO;
  - **else if** (b_{l_r}) **then return** LEFTONE_RIGHTONE;
- **case** $\Delta_{trx}= 3$:
  - **if** (trx_{left}> trx_{right})
    - **if** ((trx_{left}> trx_{right}+3) **and** b_l) **then return** LEFTTHREE ;
    - **else if** ($b_{l\_l\_r}$) **then return** LEFTTWO_RIGHTONE;
  - **else if** (trx_{right}> trx_{left})
    - **if** ((trx_{right}> trx_{left}+3) **and** b_r) **then return** RIGHTTHREE ;
    - **else if** ($b_{l\_r\_r}$) **then return** LEFTONE_RIGHTTWO;
  - **else**
    - assign j the value *module*(*random*(), 2);

– **if** ((j =0) **and** $b_{l\_l\_r}$) **then return** LEFTTWO_RIGHTONE; – **else if** ((j=1) **and** $b_{l\_r\_r}$) **then return** LEFTONE_RIGHTTWO; – **if** nothing is returned, **repeat** the three steps above till a value is returned

It can be seen here that, differently from the Deterministic option, there is not any pre-decided hierarchy. Instead, before deciding the configuration to give to the new transceivers, the algorithm becomes aware which is the situation in the adjacencies of the lightpath of interest. In the particular case that the left counter is equivalent to the right counter, the random function is called.

Finally, the Packing Superchannel Grooming option algorithm is reported below.

	Input
	– lightpath *curr_lp* . Let us remember that *curr_lp* stores its possibilities to groom the incoming connection request on top of itself through the booleans $b_{electronicOnly}$, b_l, b_r, b_{l_r}, $b_{l\_l\_r}$ and $b_{l\_r\_r}$ – number of transponders to be added Δ_{trx}. Possible values of $\Delta_{trx}$are $\Delta_{trx} \epsilon \{1, 2, 3\}$;
	Output
	– configuration of the new transponders: where they have to be added. Possible values: LEFTONE, RIGHTONE, LEFTONE_RIGHTONE, LEFTTWO, … and so on
	Variables
	– $cntr_{left}$= 0 ; – $cntr_{right}$= 0 ; – trx_{left}= 0 ; – trx_{right}= 0 ; – j = 0 ;
	Algorithm
1:	– count the number of spectrum slices at the left of *curr_lp* that are not allocated and can accommodate eventual additional

transponders. A spectrum slice is to be considered allocated if it is allocated in any of the fibers belonging to *curr_lp* . Assign this value to $cntr_{left}$;

- count the number of spectrum slices at the right of *curr_lp* that are not allocated and can accommodate eventual additional transponders. Assign this value to $cntr_{right}$;
- from the value of $cntr_{left}$, derivate the number of transponders that can actually be installed upon such number of spectrum slices. Assign this value to trx_{left};
- from the value of $cntr_{right}$, derivate the number of transponders that can actually be installed upon such number of spectrum slices. Assign this value to trx_{right};
- **go to** the next step according to the value of Δ_{trx};
- **case** $\Delta_{trx}= 1$:
  - **if** (($trx_{left} < trx_{right}$) **and** b_l) **then return** LEFTONE ;
  - **else if** (($trx_{right} < trx_{left}$) **and** b_r) **then return** RIGHTONE;
  - **else**
    - assign j the value *mod*(*random*(), 2);
    - **if** ((j =0) **and** b_l) **then return** LEFTONE;
    - **else if** ((j=1) **and** b_r) **then return** RIGHTONE;
    - **if** nothing is returned, **repeat** the three steps above till a value is returned
- **case** $\Delta_{trx}= 2$:
  - **if** (($trx_{left} < trx_{right}$) **and** b_l) **then return** LEFTTWO ;
  - **else if** (($trx_{right} < trx_{left}$) **and** b_r) **then return** RIGHTTWO;
  - **else if** (b_{l_r}) **then return** LEFTONE_RIGHTONE;
  - **else**
    - assign j the value *mod*(*random*(), 3);
    - **if** ((j =0) **and** b_l) **then return** LEFTTWO;
    - **else if** ((j=1) **and** b_r) **then return** RIGHTTWO;
    - **else if** ((j=2) **and** b_{l_r}) **then return** LEFTONE_RIGHTONE;

- **if** nothing is returned, **repeat** the four stesp above till a value is returned
- **case** $\Delta_{trx} = 3$:
  - **if** ((trx_{left}< trx_{right}) **and** (b_l **or** $b_{l\_l\_r}$**or** $b_{l\_r\_r}$))
    - **if** (b_l) **then return** LEFTTHREE;
    - **else if** ($b_{l\_l\_r}$) **then return** LEFTTWO_RIGHTONE;
    - **else if** ($b_{l\_r\_r}$) **then return** LEFTONE_RIGHTTWO;
  - **else if** ((trx_{right}< trx_{left}) **and** (b_r**or** $b_{l\_r\_r}$**or** $b_{l\_l\_r}$))
    - **if** (b_r) **then return** RIGHTTHREE;
    - **else if** ($b_{l\_r\_r}$) **then return** LEFTONE_RIGHTTWO;
    - **else if** ($b_{l\_l\_r}$) **then return** LEFTTWO_RIGHTONE;
  - **else**
    - assign j the value *mod*(*random*(), 4);
    - **if** ((j =0) **and** b_l) **then return** LEFTTHREE;
    - **else if** ((j=1) **and** b_r) **then return** RIGHTTHREE;
    - **else if** ((j=2) **and** $b_{l\_l\_r}$) **then return** LEFTTWO_RIGHTONE;
    - **else if** ((j=3) **and** $b_{l\_r\_r}$) **then return** LEFTONE_RIGHTTWO;
    - **if** nothing is returned, **repeat** the five steps above till a value is returned

4.10 Superchannel Release

Analogously to the Superchannel Grooming, also for the Superchannel release three options can be explored. They bear the same names as above, since they follow the same principles: **Deterministic**, **Holing** or **Packing Superchannel Release**. With superchannel release we meane the process of subtracting transceivers from an installed frequency slot due to the departure of one of the connections exploiting it. When the connection accommodated over the frequency slot is only one, its departure implies the release of the whole lightpath (thus guardbands included, if not shared with another frequency slot).

Deterministic Superchannel Release option disregards the situation in the two (left and right) adjacent portions of spectrum. Holing tries to level up the probabilities of the left and right frequencies slot to host a future superchannel grooming. Hence, as drawback, it penalizes the probability of being groomed for high bandwidth-requiring connection requests (that is, demanding for a high number of spectrum slices). On the contrary, the Packing option favourites the farther frequency slot of the two, that is the one having the higher number of spectrum slices as gap between itself and the frequency slot under consideration. The Packing option tries to leave such gap untouched, in order to favourite future grooming over such frequency slot.

All the three options take into account the number of transceivers that are to be released and return the configuration of how the release will occur. As above, in the Packing and Holing options will appear also two counters: one for the left side and one for the right side. They will count the number of consecutive free spectrum slices on the left and right side, respectively. They will thus express the dimensions of the "holes" in the adjacent spectrum towards lower and higher frequencies, respectively. We start reporting the algorithm given for the Deterministic Superchannel Release option here below.

Input

- number of transponders to be removed Δ_{trx}. Possible values of Δ_{trx} are MINUS1, MINUS2 and MINUS3

Output

- configuration of the transponders removal : where they have to be removed. Possible values: LEFTONE, RIGHTONE, LEFTONE_RIGHTONE, LEFTTWO, … and so on

Algorithm

- **go to** the next step according to the value of Δ_{trx};
- **case** PLUS1
  - **return** LEFTONE;
- **case** PLUS2
  - **return** LEFTONE_RIGHTONE;

– **case** PLUS3
  - **return** LEFTTWO_RIGHTONE;

It can be seen that, given the number of transponders to be released, the configuration of such release set a priori and returned. The configurations of the superchannel releases, given they unawareness of the adjacent situation, tries to be fair subdividing the making of free spectrum between the two sides.

For the Holing Superchannel Release that algorithm is defined as follows.

Input

– number of transponders to be removed Δ_{trx}. Possible values of Δ_{trx} are MINUS1, MINUS2 and MINUS3

Output

– configuration of the transponders removal : where they have to be removed. Possible values: LEFTONE, RIGHTONE, LEFTONE_RIGHTONE, LEFTTWO, … and so on

Variables

– $cntr_{left}$= 0 ;
– $cntr_{right}$= 0 ;
– trx_{left}= 0 ;
– trx_{right}= 0 ;
– j = 0 ;

Algorithm

– count the number of frequency slots at the left of *curr_lp* that are not allocated and can accommodate eventual additional transponders. A frequency slot is to be considered allocated if it is allocated in any of the fibers belonging to *curr_lp* . Assign this value to $cntr_{left}$;
– count the number of frequency slots at the right of *curr_lp* that are not allocated and can accommodate eventual additional transponders. Assign this value to $cntr_{right}$;
– from the value of $cntr_{left}$, derivate the number of transponders that can actually be installed upon such number of frequency slots. Assign this value to trx_{left};

- from the value of $cntr_{right}$, derivate the number of transponders that can actually be installed upon such number of frequency slots. Assign this value to trx_{right};
- **go to** the next step according to the value of Δ_{trx};
- **case** MINUS1
    - **if** (trx_{left}< trx_{right}) **then return** LEFTONE ;
    - **else if** (trx_{right}< trx_{left}) **then return** RIGHTONE;
    - **else**
        - assign j the value *mod*(*random*(), 2);
        - **if** (j =0) **then return** LEFTONE;
        - **else if** (j=1) **then return** RIGHTONE;
- **case** MINUS2
    - **if** (trx_{left}> trx_{right}) **then return** LEFTTWO ;
    - **else if** (trx_{right}> trx_{left}) **then return** RIGHTTWO;
    - **else return** LEFTONE_RIGHTONE;
- **case** MINUS3
    - **if** (trx_{left}> trx_{right})
        - **if** ((trx_{left}> trx_{right}+3) **then return** RIGHTTHREE ;
        - **else return** LEFTONE_RIGHTTWO;
    - **else if** (trx_{right}> trx_{left})
        - **if** (trx_{right}> trx_{left}+3) **then return** LEFTTHREE ;
        - **else return** LEFTTWO_RIGHTONE;
    - **else**
        - assign j the value *mod*(*random*(), 2);
        - **if** (j =0) **then return** LEFTTWO_RIGHTONE;
        - **else return** LEFTONE_RIGHTTWO;

It can be seen how, according to the values of the two counters, the free spectrum in created in both sides with the aim of leveling up the difference in width between the two “holes”.

Finally, we report the algorithm executed when the Superchannel Release parameter is set with the option Packing.

Input

- number of transponders to be removed Δ_{trx}. Possible values of Δ_{trx} are MINUS1, MINUS2 and MINUS3

Output

- configuration of the transponders removal : where they have to be removed. Possible values: LEFTONE, RIGHTONE, LEFTONE_RIGHTONE, LEFTTWO, … and so on

Variables

- $cntr_{left}$= 0 ;
- $cntr_{right}$= 0 ;
- trx_{left}= 0 ;
- trx_{right}= 0 ;
- j = 0 ;

Algorithm

- count the number of frequency slots at the left of *curr_lp* that are not allocated and can accommodate eventual additional transponders. A frequency slot is to be considered allocated if it is allocated in any of the fibers belonging to *curr_lp* . Assign this value to $cntr_{left}$;
- count the number of frequency slots at the right of *curr_lp* that are not allocated and can accommodate eventual additional transponders. Assign this value to $cntr_{right}$;
- from the value of $cntr_{left}$, derivate the number of transponders that can actually be installed upon such number of frequency slots. Assign this value to trx_{left};
- from the value of $cntr_{right}$, derivate the number of transponders that can actually be installed upon such number of frequency slots. Assign this value to trx_{right};
- **go to** the next step according to the value of Δ_{trx};
- **case** MINUS1
    - **if** (trx_{left}> trx_{right}) **then return** LEFTONE ;
    - **else if** (trx_{right}> trx_{left}) **then return** RIGHTONE;
    - **else**

- assign j the value *module*(*random*(), 2);
- **if** (j =0) **then return** LEFTONE;
- **else return** RIGHTONE;

- **case** MINUS2
  - **if** (trx_{left}> trx_{right}) **then return** LEFTTWO ;
  - **else if** (trx_{right}> trx_{left}) **then return** RIGHTTWO;
  - **else**
    - assign j the value *mod*(*random*(), 2);
    - **if** (j =0) **then return** LEFTTWO;
    - **else return** RIGHTTWO;
- **case** MINUS3
  - **if** (trx_{left}> trx_{right}) **then return** LEFTTHREE ;
  - **else if** (trx_{right}> trx_{left}) **then return** RIGHTTHREE ;
  - **else**
    - assign j the value *mod*(*random*(), 2);
    - **if** (j =0) **then return** LEFTTHREE;
    - **else return** RIGHTTHREE;

It can be observed that all the transponders to be release are released on the same side. If one side presents a bigger hole than the other, that will be the chosen side where to release transceiver. Eventually, is both “holes” present the same width, the picked one is chosen randomly.

4.11 Set of Statistics as Output

Whilst in the previous Sections we have described the functioning of the algorithm and explained in detail all the possible policies that can be provide to it as inputs, in this Section we are going to focus on the output of the RSA algorithm. The statistics provided as outputs by the algorithm are going to be the topic of the Paragraph.

First of all, the **blocking probability** p_{block} is provided. It is defined as:

$$p_{block} = \frac{number\ of\ dropped\ connection\ requests}{total\ number\ of\ arrived\ connection\ requests},$$

or, equivalently,

$$p_{block} = 1 - \frac{number\ of\ setup\ connection\ requests}{total\ number\ of\ arrived\ connection\ requests}.$$

Then, the **bandwidth utilization** bw_{util} is given. It is defined as:

$$bw_{util} = \frac{spectrum\ utilized}{total\ spectrum\ available}.$$

It can be calculated in two different ways, according whether we are in the DWDM rather than in the flexible grid scenario. In the former case, it can be derived as

$$bw_{util}^{DWDM} = \frac{number\ of\ utilized\ channels}{total\ number\ of\ available\ channels},$$

while when in the flexible grid scenario its derivation is as follows

$$bw_{util}^{flexi} = \frac{nr\ of\ spectrum\ slices\ allocated\ with\ traffic + nr\ of\ spectrum\ slices\ utilized\ as\ guardbands}{total\ number\ of\ available\ spectrum\ slices}.$$

Another statistic provided as output is the **traffic bandwidth utilization**, which is defined analogously as the previous statistic but will take into account the part of spectrum utilized for traffic allocation only. Thus

$$bw_{util\_traff} = \frac{spectrum\ utilized\ for\ traffic}{total\ spectrum\ available}.$$

In a network utilizing the DWDM technology it will thus be calculated as

$$bw_{util\_traff}^{DWDM} = \frac{number\ of\ utilized\ channels * 0.56}{total\ number\ of\ available\ channels},$$

where the 0.56 is given as the fixed portion of the DWDM channel actually occupied by the transceiver, that is 28 GHz of the channel width equal to 50 GHz.

When exploiting the possibilities offered by flexible grid instead, the traffic bandwidth utilization is calculated as

$$bw_{util\_traff}^{flexi} = \frac{nr\ of\ spectrum\ slices\ allocated\ with\ traffic}{total\ number\ of\ available\ spectrum\ slices}.$$

Compared with the bw_{util}^{DWDM}, it can be noticed how the spectrum slices utilized as guardbands are excluded by the summation at the numerator of the ratio.

Another statistic which takes into account the difference between the spectrum utilized for traffic allocation and spectrum exploited as guardband is the **relative guardband bandwidth utilization**. Defined as

$$bw_{util\_guardb} = \frac{spectrum\ utilized\ as\ guardbanbd}{total\ utilzed\ spectrum},$$

it expresses how the guardbands affect the efficient utilization of the available spectrum. This parameter is constant in DWDM networks,

$$bw_{util\_guardb}^{DWDM} = \frac{number\ of\ utilized\ channels * 0.44}{number\ of\ utilized\ channels} = 0.44\ ,$$

where the figure 0.44 is given by the bilateral guarbdands of 11 GHz per side present in each 50-GHz wide channel. In the flexible grid scenario, it can be calculated as

$$bw_{util_{guardb}}^{flexi} = \frac{nr\ of\ spectrum\ slices\ utilized\ as\ guardband}{total\ number\ of\ utilized\ spectrum\ slices} =$$

$$= \frac{nr\ of\ spectrum\ slices\ utilzed\ as\ guardband}{nr\ of\ spectrum\ slices\ utilized\ as\ guardband + nr\ of\ spectrum\ slices\ allocated\ as\ traffic}.$$

When forming superchannels, the efficiency of spectrum utilization increases since portions of spectrum required as guardbands decrease. So, this statistic $bw_{util\_guardb}^{flexi}$ expresses how efficiently the superchannels are formed.

Another statistic provided as output from the algorithm is the **average number of utilized transponders** $\overline{trx}$. This statistic will help quantifying the impact of the two weights α and β of the objective function

Finally, an important statistic which is provided for flexible networks only is the **fragmentation ratio** f_{rat}. Introduced in [76], it is an indicator of how fragmented the spectrum is on a link. It is thus calculated per link and then averaged over the total number of links. The fragmentation ratio does not make sense in a DWDM network, where the channels are considered independently from each other. In flexible network instead, with the introduction of bandwidth-variable frequency slots, the spectrum can be considered as a continuum and the allocation of frequency slots on it impacts on its fragmentation. In order to define f_{rat}, the available spectrum slices are organized in contiguous **blocks**. Let (G_1, G_2, …, G_i, …) denote the sizes of the blocks. An example is represented in Figure 32 where three different blocks are present having sizes G_1=7, G_2=3, G_3=7.

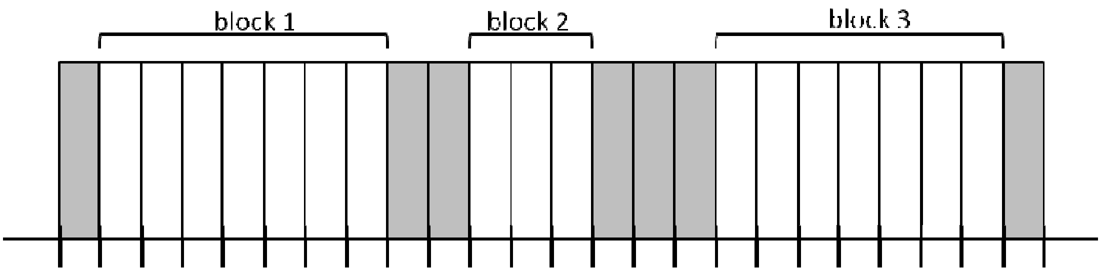

Figure 32. Three different blocks of contiguous available spectrum slices. Gray spectrum slices are not available.

Then per each block its **value** $v(G_i)$ is defined as the maximal data rate that can be provisioned using it. In order to have a univocal definition of f_{rat}, disregarding form the modulation format used on the links, we can define the value of each block as the maximum number of spectrum slices that can be utilized for traffic allocation, that is a transponder can be allocated on them. For each block we thus have to exclude two spectrum slices to be adopted as guarbdands, one per side. Still referring to Figure 32, we thus have the first block having value $v(G_1)$=5, the second block having value $v(G_2)$=1, while the third and last block with value $v(G_3)$=5. This definition of value is outside of the assumption A.7 of fixed bandwidth transponders occupying five spectrum slices, but it gives a more precise information upon the real fragmentation of the spectrum. We have now all the elements to define the fragmentation ratio as

$$f_{rat} = 1 - \frac{\sum_i v(G_i)}{v(\sum_i G_i)}.$$

At the numerator is the actual value of the available spectrum slices for traffic allocation, at the denominator the potential value of spectrum slices allocable for traffic in the hypothesis that all the blocks were contiguous to each other.

Since with assumption A.8 we did not put any limit in the number of transponders that can be set adjacently in order to form a superchannel, there is hypothetically no limitation in the width of a frequency slot; as a result at the denominator will appear the total number of free spectrum slices on the link subtracted by two, which are the two lateral guardbands of this extended frequency slot. It is now intuitive the meaning of this statistics: the closer the f_{rat} is, the less fragmented is the spectrum.

5 Benefits of Flexible Grid over WDM

After having introduced in Chapter 2 the development of technological solutions for the metro access networks, we have exposed in Chapter 3 the network model which is going to be adopted for the RSA and RMLSA algorithms. In Chapter 4 the RSA algorithm is presented to the reader with a particular focus on the difference functioning for the set of policies that can be provided as inputs.

Before analyzing the impact of these inputs on the statistics given as outputs, in this Chapter we carry out an analysis of the benefits brought from a flexible grid solution if compared with legacy DWDM technology. The performances of the two technologies are both derived considering the two possibilities of performing traffic grooming or not. Thus four scenarios are compared in this analysis:

- DWDM network exploiting the possibility of grooming
- DWDM network not capable of performing grooming
- Flexible grid network with the possibility of grooming
- Flexible grid network without grooming capabilities

The four scenarios are explored in both traffic distribution hypotheses, Uniform and Not Uniform. Each traffic distribution, in turn, is analyzed for both dimensions of the objective function, that is the minimization of either the spectrum occupation or the utilization of transponders. The clockwise vs counterclockwise tie resolution policy will be equally set for all scenarios to the option: Least Used Link. The remaining policies, that are spectrum assignment together with superchannel grooming and release, are valid in flexible network only, while they are not present for the DWDM solution. With regard to the spectrum assignment, when performing the RSA algorithm over a flexible network such policy will be set at the Random option. Both superchannel grooming and superchannel release policies will be set at the Holing option.

5.1 Results and discussions

After this preliminary introduction, we can now go exploring the impact of the flexible grid solution over DWDM technology. All the statistics provided as output from the algorithm will be compared for the two traffic distributions, except for the fragmentation index which, as previously explained, is meaningless in DWDM networks.

The offered load will be varied from 50 to 1000 Erlangs by steps of 50 Erlangs. The average required load per request is set to 160 Gbit/s. The DP-QPSK is assumed as sole modulation format.

5.1.1 Blocking probability

A very important indicator of the network performance is the blocking probability for an incoming connection request. For not uniform traffic distribution, the results in terms of blocking probability are illustrated in Figure 33 hereafter. Eventual blocking probability below 10^{-5} is ignored.

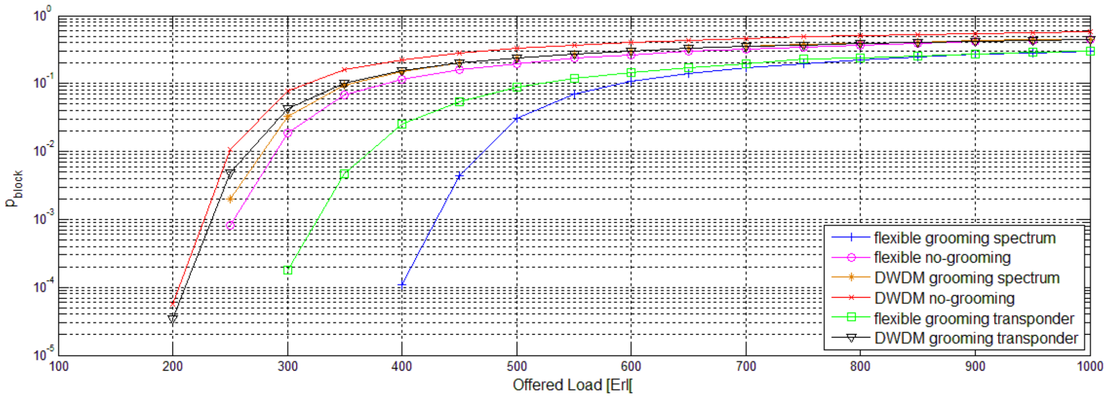

Figure 33. Blocking probability for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization).

Figure 33 illustrates the important benefits brought by the adoption of flexible technology innovation. In fact, all the four possibilities for the flexible network present better performance than the best option for DWDM network (capable of grooming and minimizing the spectrum utilization, orange line) in terms of blocking probability.

Comparing the best option for DWDM network with the best option for flexible grid technology (blue line), for instance when the offered load is equal to 400 Erl it can be seen as the latter has a blocking probability ($\sim 10^{-4}$) which is three orders of magnitude smaller with respect to the former ($\sim 10^{-1}$). At the same offered load, a flexible solution minimizing the utilization of transponders (green line), it still improves the blocking probability compared to DWDM, but the benefit is lower ($p_{block} \cong 2 * 10^{-2}$). Finally, the two flexible options that do not exploit the grooming capability are not undistinguishable and both represented by the purple line. Their blocking probability is very similar to the best DWDM option, even though smaller. Moreover, also the two DWDM scenario not exploiting the grooming capability are represented by a single line (red line). A closer glance for low offered loads is provided in Figure 34.

An important feature which is highlighted by Figure 34 is the much bigger impact that has the grooming capability in the flexible network if compared with the DWDM technology. In fact, the key improvement brought by the exploitation of a flexible grid is the introduction of superchannels. They allow to spare the fixed-bandwidth guardbands put at both sides of the transponder in each channel; when forming the superchannel, only the two external guardbands are present but the intra-superchannel guardbands (those between adjacent transponders belonging to the same super-channel) can be neglected. Thus, whilst in traditional DWDM networks the grooming capability allows to add traffic over under-utilized transponders but each channel remains independent from the others, in flexible networks the further spectrum saving due to formation of superchannels is present. This explains why, for an objective function of spectrum minimization into a flexible network, the introduction of the grooming capability leads to an improvement of roughly three orders of magnitude (for an average load of 400 Erl from $p_{block} \cong 10^{-1}$ to $p_{block} \cong 10^{-4}$). On the other hand, in DWDM ring networks the possibility of exploiting the grooming feature yields to much smaller improvement: the average load still being 400 Erl, a blocking probability of $\sim 2 * 10^{-1}$ is only slightly improved to $p_{block} \cong 10^{-1}$.

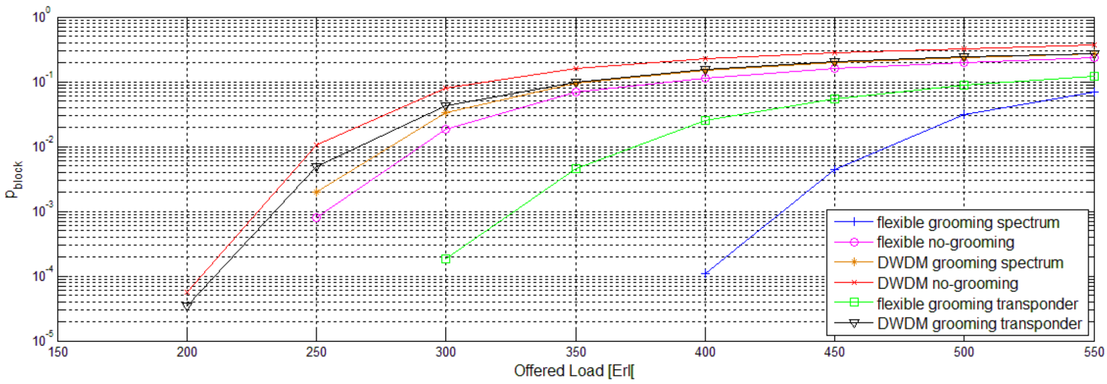

Figure 34. Detail of Fig. 32. Offered traffic varies from 150 to 550 Erl.

We can now analyze how the result changes when modifying the traffic distribution. In Figure 35, the blocking probability under the hypothesis of uniform traffic distribution is illustrated.

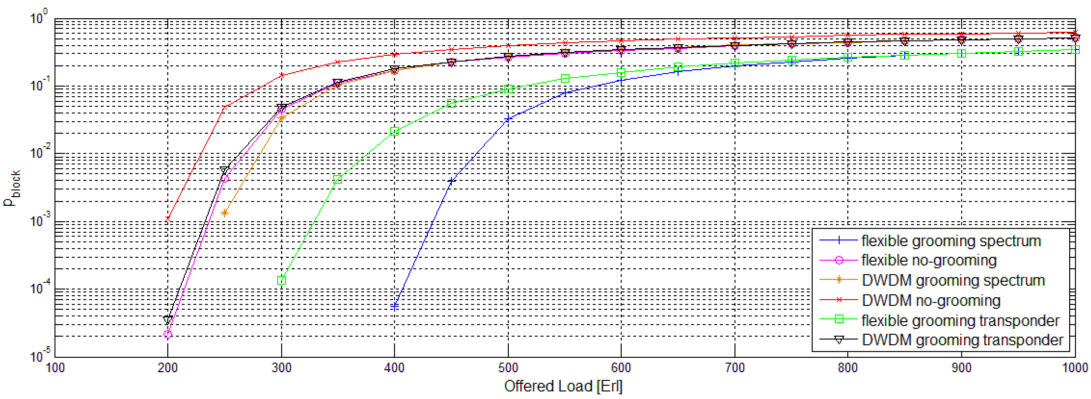

Figure 35. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

Under the assumption of uniform traffic distribution, when compared with the not uniform one, the possibility of having fractional bandwidth requests is higher. With fractional bandwidth request we hereafter intend a connection request which demands for an amount of bandwidth that does not occupy entirely the transponders to be allocated. So a connection requiring 60 Gbit/s, or equally 3 spectrum slices, is what we here consider fractional, while a connection requiring 5 or 10 spectrum slices (100 Gbit/s or 200 Gbit/s, equivalently) is not to be considered fractional. Said so, a higher probability of fractional connection requests leads to higher inefficiency in spectrum occupation when the network is not grooming capable.

As a result, the introduction of grooming capability brings more important improvements, if compared with the not-uniform traffic distribution scenario. For an offered load of 400 Erl, a not-grooming flexible network has a blocking probability of $\sim 2 * 10^{-1}$; its performance is dramatically improved to $p_{block} \cong 5 * 10^{-5}$ when introducing grooming. Furthermore, when taking into consideration the grooming and not-grooming alternatives for the DWDM network, the uniform traffic distribution scenario experiences better improvements also for this transmission technology, but it is noticeable for lower average loads. In Figure 33 related to the not uniform traffic distribution, for an average load of 250 Erl the blocking probability improves from $p_{block} \cong 10^{-2}$ to $p_{block} \cong 10^{-3}$ upon the introduction of the grooming capability. In the current scenario of uniform traffic distribution instead (Figure 35), still for an average load of 250 Erl, the addition of the grooming capability brings an improvement from $p_{block} \cong 5 * 10^{-2}$ to $p_{block} \cong 10^{-3}$. The final figure is similar, but the improvement is more consistent.

When analyzing the two scenarios for high offered loads of traffic instead, that is with almost saturated network, we can notice how Figure 33 and Figure 35 show both the same flat behavior on the right-hand part of the graph. The DWDM not-grooming-capable is the solution with the worst performance, due to inefficiency in underused transceiver (fractional requests) and the fixed-bandwidth bilateral guardband always present in each channel. In fact, in the DWDM solution the channels are treated independently one from the other. A second region of flat growth gathers together the behavior of the grooming-capable DWDM solutions and the scenarios of flexible grid without grooming capability. A final flat growth, which is the one with the best performance, is identified for the solution exploiting both the flexible network innovation and the grooming capability. It can be noticed that, at network saturation, the two lines referred to the flexible grid network minimizing either the spectrum occupation or the transponders are not distinguishable one from the other.

Finally, we report in Figure 36 still the blocking probability for uniform traffic distribution, but focusing on low values of offered load. In this figure it is outlined the importance of grooming capability for such traffic distribution. The improvement brought by the introduction of the grooming feature produces similar advantages to the case of exploitation of a flexible grid rather than the a DWDM spacing pattern. The curve referring to a not-grooming-capable flexible network (purple line) lies above the DWDM grooming capable network aiming to minimize the spectrum occupation (orange line). It means that, under the hypothesis of uniform traffic distribution, to deprive the flexible network of the grooming capability has more dramatic effects than switching from elastic grid back to a DWDM system.

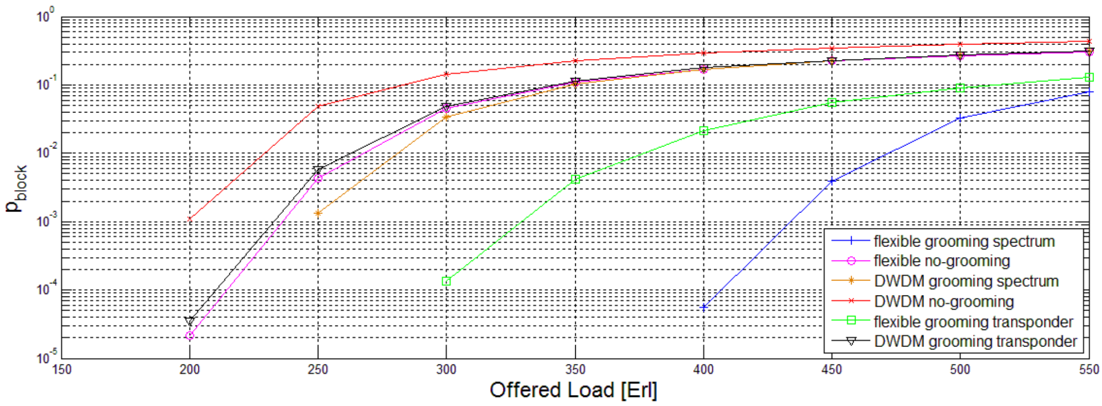

Figure 36. Detail of Fig. 34. Offered traffic varies from 150 to 550 Erl

We can conclude these two analysis summarizing what has been outlined in this Subsection. A ring network exploiting the innovative flexible grid solution instead of the traditional DWDM transmission system presents better performances with regard to the blocking probability of an incoming connection request. The improvement in performances can be quantified with two or three orders of magnitude for scarcely loaded network. This improvement can be expected to be given from a more efficient utilization of available spectrum resources thanks to the flexibility in spectrum width of the frequency slots, in our case represented by the possibility of forming superchannels. Several DWDM channels having the same source destination pair are grouped together into a single entity, the superchannel, and intra-superchannel guardbands are spared.

5.1.2 Bandwidth utilization

In this Subsection we see the bandwidth utilization statistic in order to provide the reader with some figures to confirm the hypothesis of better utilization of spectrum resources with the introduction of superchannels. In Figure 37 the scenario assuming a not uniform bandwidth distribution is illustrated, while in Figure 38 the uniform bandwidth distribution is shown.

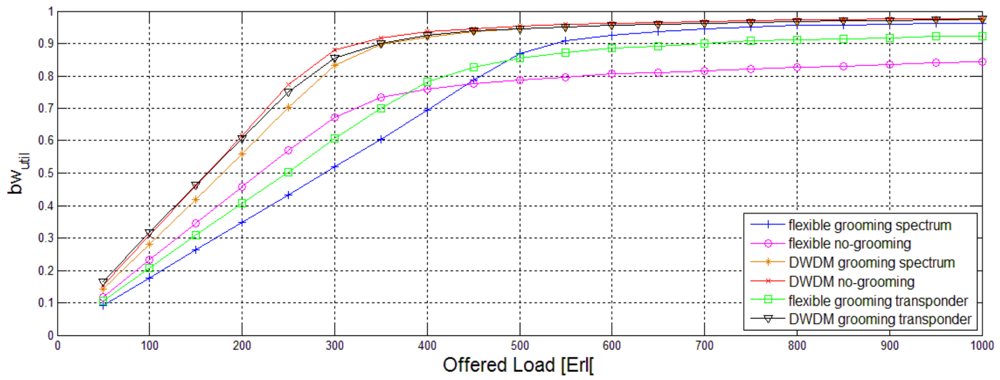

Figure 37. Bandwidth utilization for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

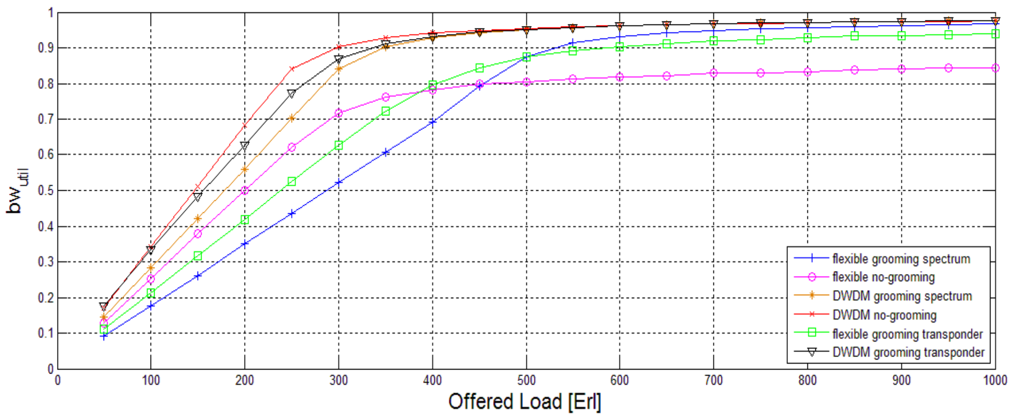

Figure 38. Bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

The two graphs have a similar behavior. In both figures, for low loads, we have the flexible network with objective function set at the minimization of spectrum occupation performing the best (i.e. consuming the least bandwidth) followed by the same solution but minimizing the number of utilized transponders. The DWDM networks not performing grooming are always those which have the highest bandwidth occupation. This is true whether the objective function minimizes the spectrum or the transceivers. Moreover, both in the DWDM and in the flexible grid scenario, when the grooming capability is not applied, to minimize the spectrum occupation rather than the transponder utilization do not imply any change in the bandwidth utilization. The two different objective functions are represented with the same curve; the purple and the red line for the flexible grid and the DWDM scenario, respectively.

When considering higher loads, we can identify a flat line grouping all the four DWDM solutions. Since in DWDM network each wavelength is treated independently, the allocation of a new connection request do not depend on how the previous requests have been allocated. As a result, the bandwidth occupation is close to 1. Three different lines are then identifiable below, and their performances are exactly the opposite if compared with the scarcely loaded situation. The grooming-capable flexible network with minimization of the occupied spectrum (blue line) occupying the most resources. The grooming-capable flexible network with minimization of the utilized transponders (green line) follows. Finally the two flexible not-grooming scenarios (purple line) are the ones occupying the most resources. The motivation behind this inversion of the three tendencies can be found in the fragmented spectrum occupation due to the objective function and to whether the grooming capability is available or not. When it is possible to groom incoming connections over already existing ones and the goal of the objective function is to minimize the spectrum occupation, a more efficient and less fragmented utilization of the optical resources is carried out, thus the spectrum on the links is better loaded. When the objective function aims to minimize the number of utilized transponders the frequency slots are allocated without particular attention to the spectrum occupation. When the grooming capability is not available, the frequency slots are sparsely allocated. In both cases, an incoming connection request is more likely dropped (as confirmed by the graphs of p_{block}); the latter case deteriorates more the performance. As a result, even if not all spectrum resources are allocated, it is not possible to setup the connection request and the unallocated spectrum remains unexploited.

5.1.3 Traffic bandwidth utilization

In order to complete the information relating to the bandwidth occupation contained in the previous Section, in the current Section we analyze the portion of spectrum utilized uniquely for traffic allocation (bw_{util_traff}). Thus the portions of spectrum used as guardband, and the portions that are left unused, are excluded. The obtained performances are reported in Figure 39, for the scenario with not uniform traffic distribution, and in Figure 40, for uniformly distributed traffic.

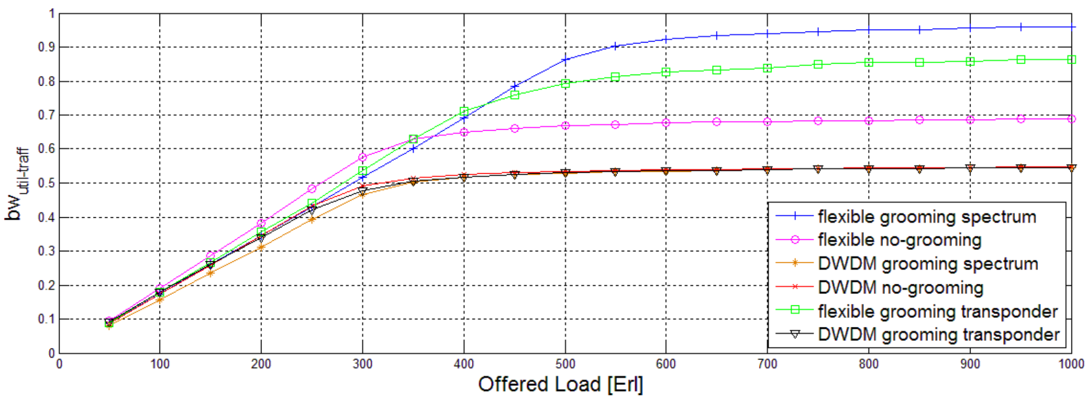

Figure 39. Traffic bandwidth utilization for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

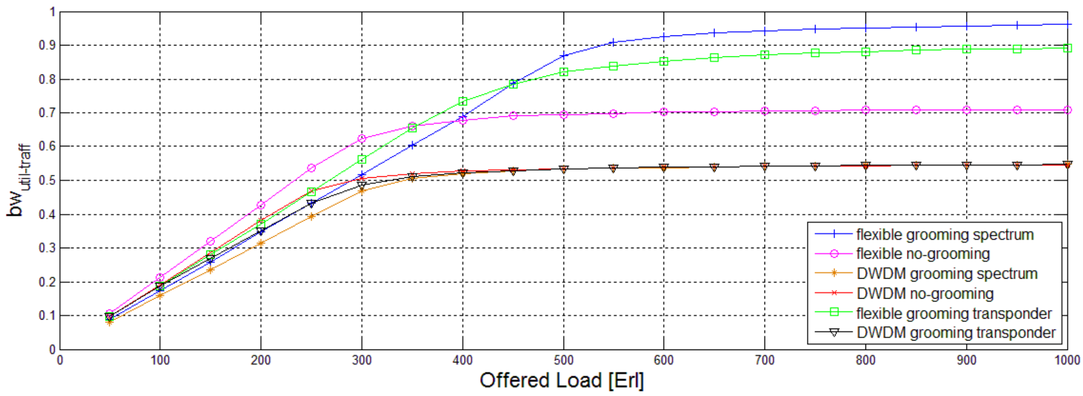

Figure 40. Traffic bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

We have seen from the two figures of the previous Section that the four options of the DWDM scenario are those that occupy the highest amount of bandwidth when the network is highly loaded. Even if the statistic bw_{util} of bandwidth utilization is almost one, the portion of spectrum that is actually utilized for spectrum allocation equals ~0.55.

This drastic decrement is not observed for the flexible network. The two not-grooming-capable flexible scenarios (purple line), still undistinguishable one from another, have a bw_{util_traff} statistic equal to ~0.71 for not uniform and uniform traffic distribution, respectively. It is lower than the value that bw_{util} assumes for both scenarios, which is ~0.85, but the decrement is not as drastic as the four DWDM options. The reason why the not uniform traffic distribution, with equal bw_{util} when compared with the uniform distribution, has a lower bw_{util_traff} figure can be explained with the fact that the former has a higher cumulative function for bandwidth requests that need only one transponder and, in the same time, those needing the allocation of more than a single transponder are not fractional but require only “full” transponders (either 200 Gbit/s or 300 Gbit/s). There are thus more “small” (single transponder) frequency slots where the impact of the guardbands is higher (5 spectrum slices at most of traffic allocation for a total spectrum occupation of 7 spectrum slices due to guardbands) and, in the same time, less underused transceivers are installed.

Finally, when analyzing the two grooming-capable flexible scenarios, we can see how their values of bw_{util_traff} do not differ in important measure from those of (total) bandwidth utilization bw_{util}. The flexible network exploiting the grooming capability and aiming to the minimization of spectrum utilization has an asymptotic value close to the unity, which means that almost all of the utilized bandwidth is used for traffic allocation. A little lower figure is obtained for the minimization of utilized transponder, but the improvement when compared with the remaining scenarios is still consistent.

5.1.4 Relative guardband bandwidth utilization

In this Subsection, we give another perspective of the two statistics analyzed in Subsection 5.1.2 and Subsection 5.1.3, that are bw_{util} and bw_{util_traff}, respectively. The results obtained for the relative guardband bandwidth utilization statistic bw_{util_guardb} are illustrated in Figure 41, where the hypothesis of not uniform traffic distribution is assumed, and in Figure 42, which is the uniformly distributed traffic scenario.

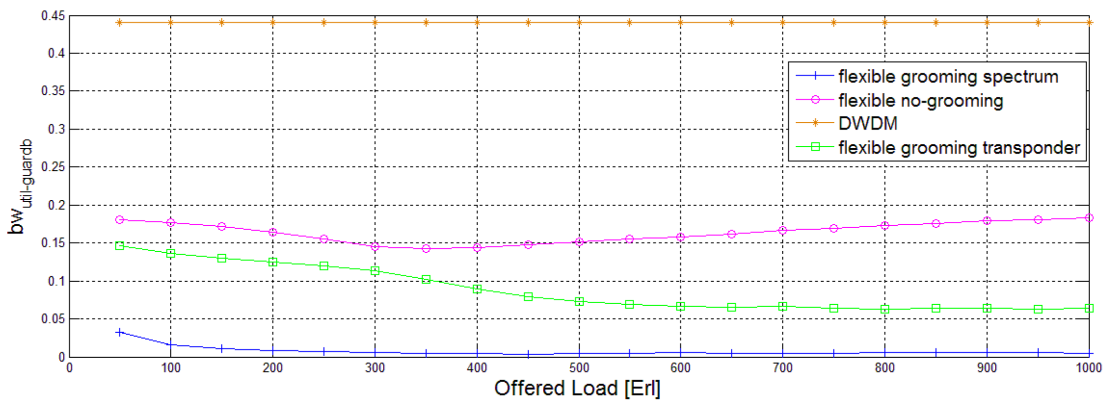

Figure 41. Relative guarband bandwidth utilization for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

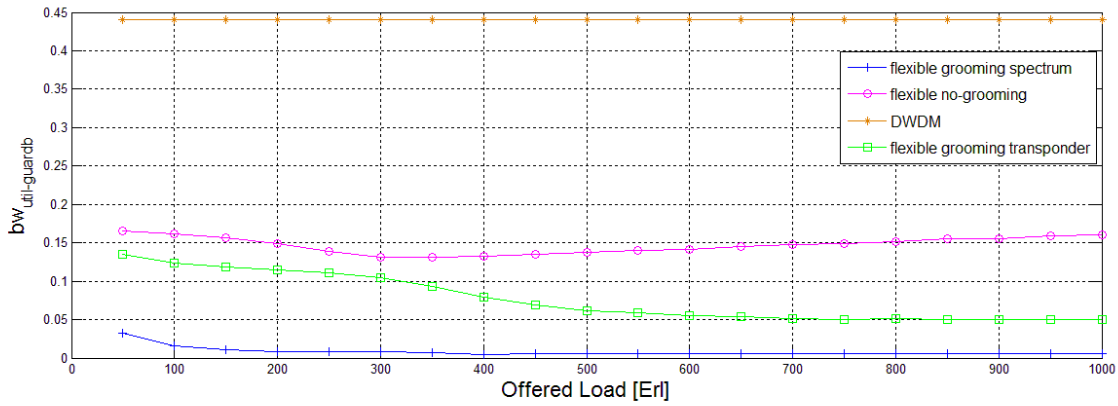

Figure 42. Relative guarband bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

It can be seen that in DWDM networks the impact of the guardbands with respect to the total occupied spectrum is constant to the value bw_{util_guardb}=0.44. This is easily deducible since each channel is made up, as previously explained, by 22 GHz used as guardband and 28 GHz utilized as optical spectrum for the allocation of the transceiver, thus of the traffic. The ratio between the two is constant and equal to 0.44, disregarding all the other channel that are installed or not.

In flexible grid the more transponders are allocated together forming a superchannel, the less impact the bilateral guardbands have with respect to the total occupied spectrum. This is why both grooming-capable flexible scenarios have a descending tendency at the increase of the offered load. More underused transponders are filled and, in the same time, wider frequency slots (i.e. superchannels) are formed. With regard to the two not-grooming-capable flexible scenario, a first decreasing tendency change with higher offered load to an increasing one. The turning point, at offered load equal to ca. 300 Erl, can be identified from Figure 37 and Figure 38 of Subsection 5.1.2 as the point where the bandwidth utilization does not increase linearly but starts to increase slower while approaching the final flat region. Thus it is the point where the network starts to be fully loaded. From this point on, connections requests will be dropped in a more significant measure which means that “small” connection requests will be privileged to be setup. Where the frequency slot is made for instance by only one transponders the impact of guardbands upon the total bandwidth consumption is more relevant.

5.1.5 Average number of utilized transponders

In this Subsection we quantify the impact of the introduction of the flexible grid, as well as the changes in the objective function and the grooming capability, on the average number of utilized transponders $\overline{trx}$. In Figure 43 the hypothesis of not uniform traffic distribution is adopted, while in Figure 44 the results obtained under the assumption of uniform traffic distribution are shown.

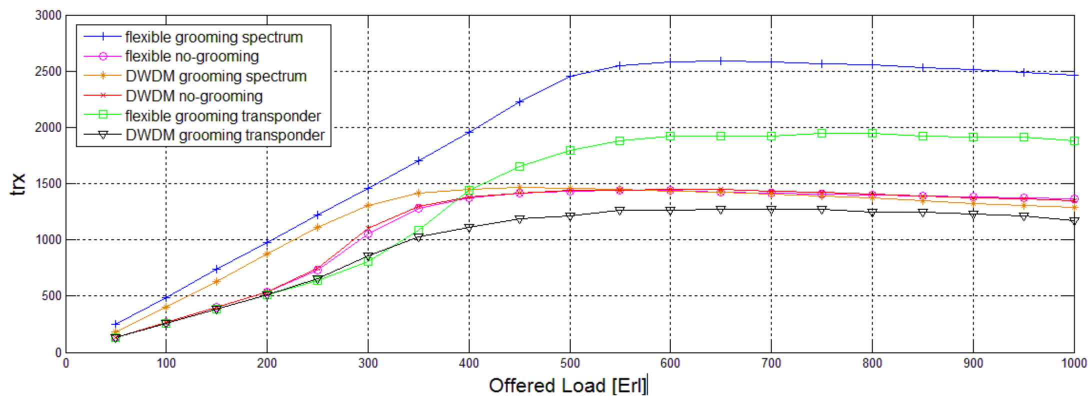

Figure 43. Average number of utilized transponders for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

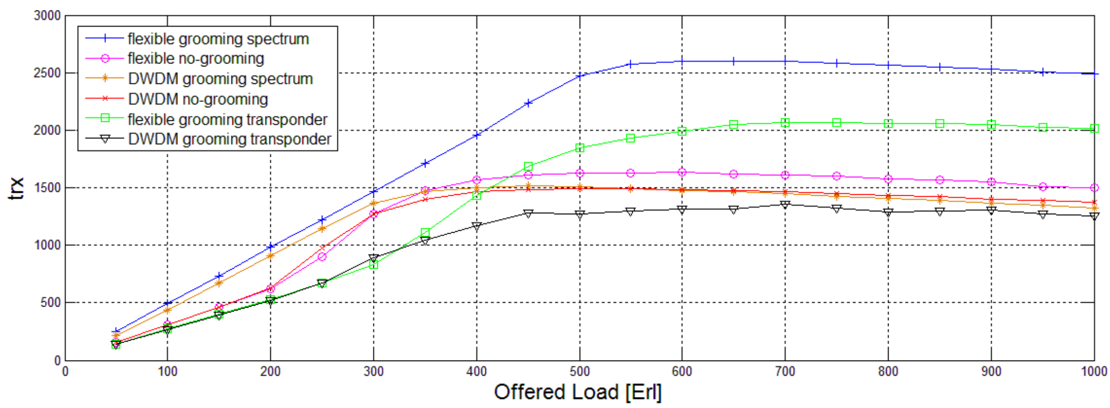

Figure 44. Average number of utilized transponders for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid vs DWDM; Grooming vs No Grooming; spectrum vs transponder minimization)

The reader can notice that, for scarcely loaded network (both DWDM and flexible grid), the scenarios with objective function set to the minimization of the number of utilized transponders and able to take advantage of the grooming capability (green line and black line) experience important savings. The scenarios with grooming capabilities which aim to minimize the spectrum occupation (blue line and orange line), consume a much higher number of transceivers. All solutions, when the network is highly loaded and the loss rate starts to affect its performance, experience a little decrease in $\overline{trx}$ for the same reasons illustrated in the previous Subsections: "small" connection requests (requiring for instance the installation of a single transponder) are more likely to be setup. The available portions of spectrum are thus more sparsely distributed among the links and, as a result, they are more hardly occupied.

5.1.6 Fragmentation ratio

In this last Subsection we report, for the sake of completion and in order to support the analysis presented before upon the performance of the flexible networks in the several statistics, the fragmentation ratio f_{rat} obtained for the flexible scenarios only. In Figure 45 the performances obtained when the assumption of not uniform traffic distribution is adopted are illustrated, while the performances obtained in Figure 46 are obtained under the assumption of uniform traffic distribution.

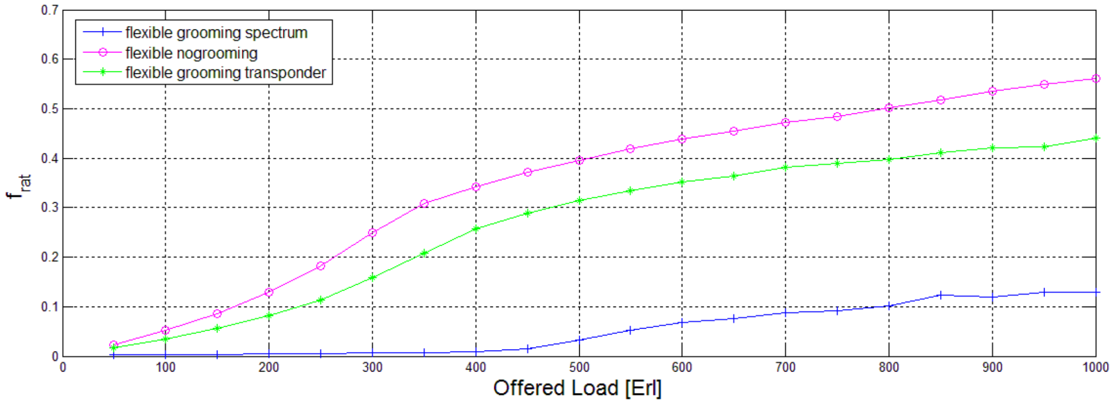

Figure 45. Fragmentation ratio for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid; Grooming vs No Grooming; spectrum vs transponder minimization)

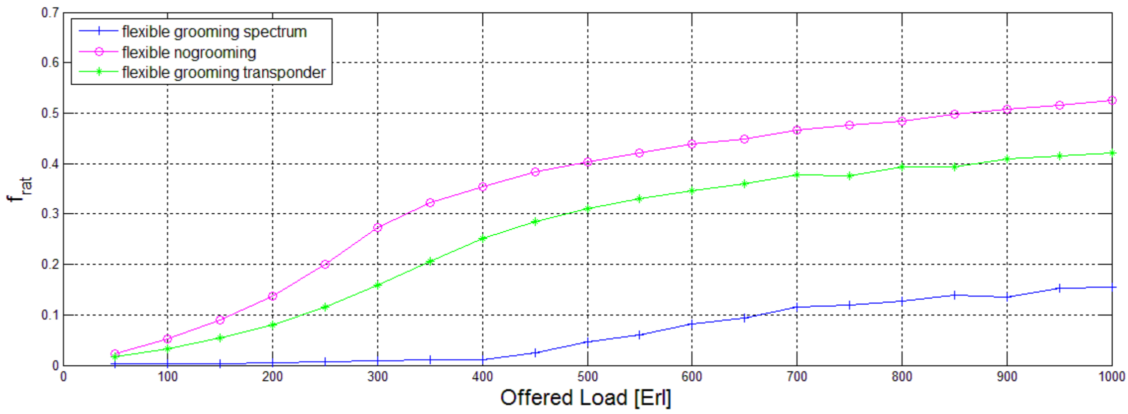

Figure 46. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Grooming vs No Grooming; spectrum vs transponder minimization)

The two figures confirm that, when the traffic grooming is not allowed and the objective function is the minimization of the utilized transponders, a more fragmented spectrum is obtained. This effect is mainly produced by the fact that no traffic grooming is allowed.

6 Impacts of Multi-Criteria in Flexible Grid

In Chapter 5 we have showed the benefits brought by the introduction of the flexible grid into a ring metro network. Moreover, we have investigated the impact of the objective function variation over the network performance.

In this Chapter we analyze the influence of the other algorithm parameters, i.e the clockwise vs counterclockwise tie resolution policy in Section 6.1, the superchannel grooming and superchannel release policies in Section 6.2, the spectrum assignment policy in Section 6.3, the objective function in Section 6.4.

6.1 Impact of Clockwise vs Counterclockwise Tie Resolution

In this Section we will compare the results obtained when varying the policy of the Clockwise vs Counterclockwise Tie Resolution parameter. Such comparison will be carried for different scenarios for the Superchannel Grooming and Superchannel Release policies in order to observe how the RSA algorithm reacts to a variation of the Clockwise vs Counterclockwise Tie Resolution option in more than a single scenario. The traffic distribution is considered as uniform and the network is assumed grooming-capable. The objective function is set to minimize the spectrum occupation (α=1, β=0.01). The spectrum assignment is accomplished according to the First Fit scheme.

In Figure 47 we only report the blocking probability as summarizing statistic of the network performance for the three options of Tie Resolution. The Superchannel Grooming is kept unchanged to the deterministic option; the Superchannel Release varies, in turn, among its three possibilities. In Figure 48 the Superchannel Grooming parameter is set to the Holing value instead and, finally, in Figure 48 to the Packing option; in both cases, the Superchannel Release policy varies among the three possibilities.

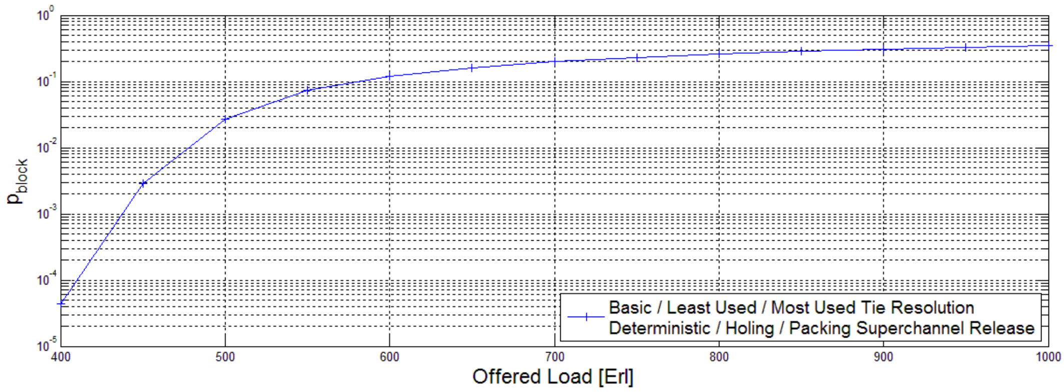

Figure 47. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Deterministic Superchannel Grooming; Basic vs Least Used Link vs Most Used Link Tie Resolution; Deterministic vs Holing vs Packing Superchannel Release)

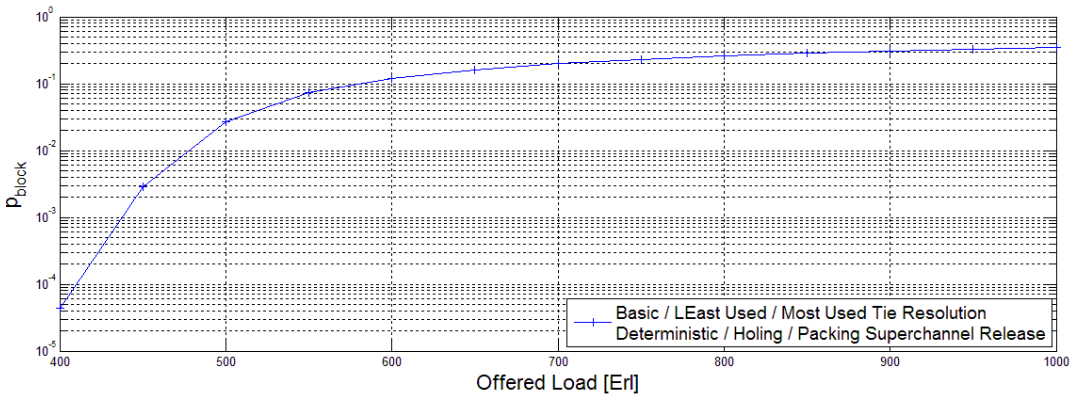

Figure 48. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Holing Superchannel Grooming; Basic vs Least Used Link vs Most Used Link Tie Resolution; Deterministic vs Holing vs Packing Superchannel Release)

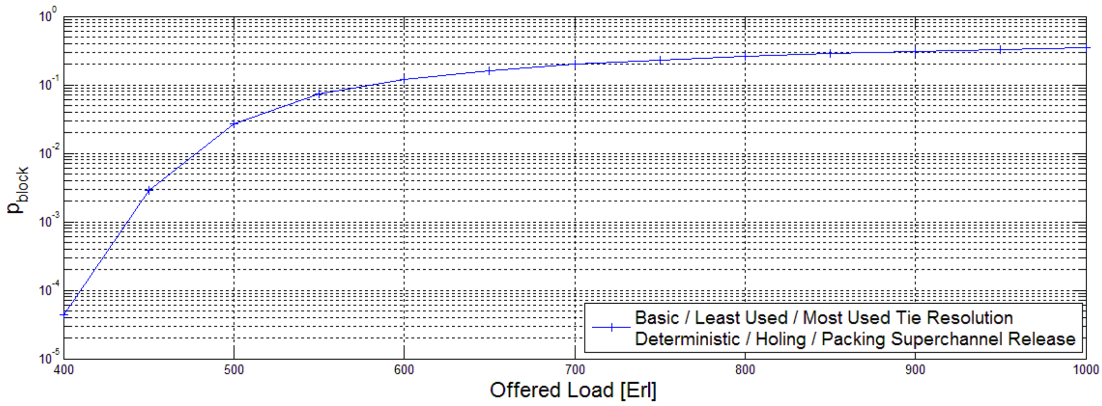

Figure 49. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Packing Superchannel Grooming; Basic vs Least Used Link vs Most Used Link Tie Resolution; Deterministic vs Holing vs Packing Superchannel Release)

In all three scenarios, even by varying the Superchannel Grooming policy, the effects of Clockwise vs Counterclockwise Tie Resolution policy are minimum and scarcely noticeable. Thus the choice to represent all the cases with a single curve.

The only statistics which is significantly influenced by the Tie Resolution policy is the fragmentation ratio, but only for highly loaded network. In Figure 50 we report the fragmentation ratio for the Deterministic Superchannel Grooming option only.

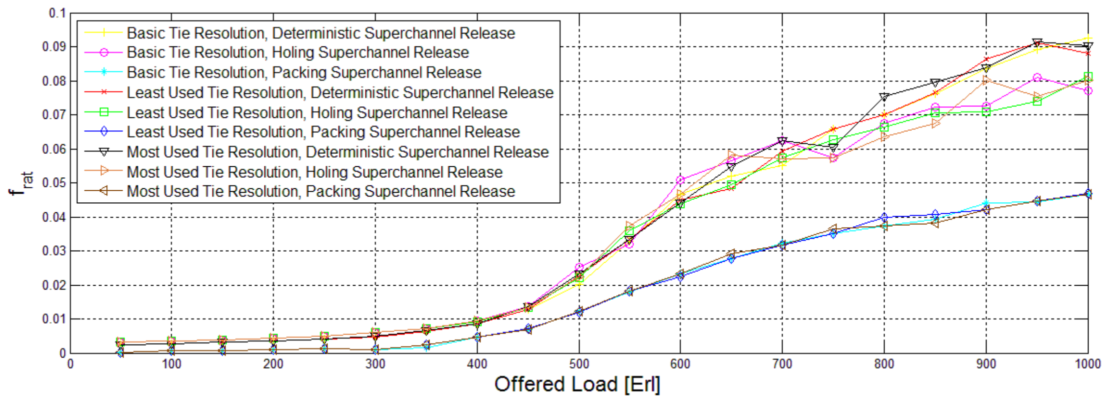

Figure 50. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Deterministic Superchannel Grooming; Basic vs Least Used Link vs Most Used Link Tie Resolution; Deterministic vs Holing vs Packing Superchannel Release)

It can be noticed, in the right-hand part of the graph, how three main tendencies can be identified according to the Superchannel Release policy. A first group, which fragments more, is relative to the Deterministic Superchannal Release policy. Just below lies the second group, is relative to the Holing Superchannel Release. Finally, a third group which fragments the least is identifiable with the Packing Superchannel Release. Inside each group there is a small influence of the Clockwise vs Counterclockwise Tie Resolution policy.

In conclusion, in this Section we can assert that the Clockwise vs Counterclockwise Tie Resolution policy scarcely influence the general performance of the network.

6.2 Impact of Superchannel Grooming and Superchannel Release

In this Section we analyze how the combination of the Superchannel Grooming and Superchannel Release policies impact on the network performance. The analysis will be carried out for three different scenarios, each characterized by a different Spectrum Assignment policy. The remaining algorithm configurations are considered as follows: the traffic is uniformly distributed, the grooming capability is available, the objective function aims to the minimization of spectrum occupation (α=1, β=0.01), in case of clockwise vs counterclockwise tie resolution the least used link policy is applied.

We can then analyze the first scenario, where the Spectrum Assignment is performed in a First Fit fashion. In Figure 51 it is illustrated how the network performs with respect to the blocking probability.

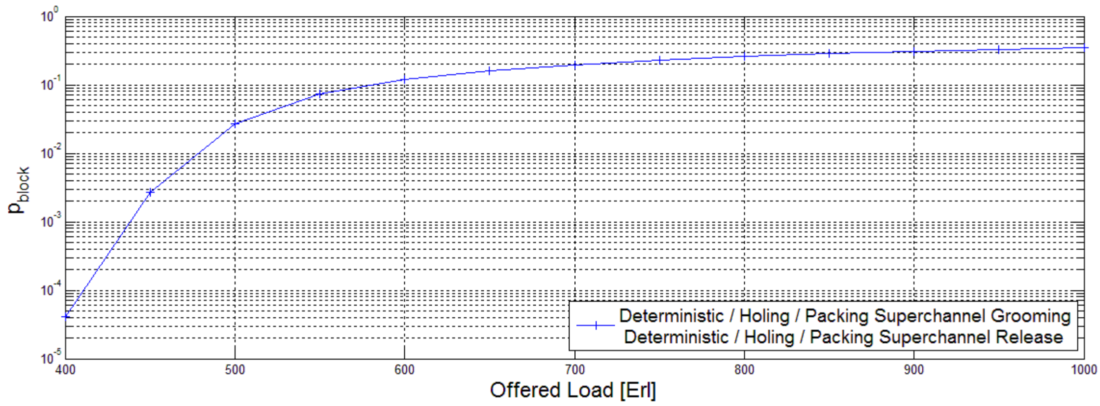

Figure 51. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assingment; Deterministic vs Holing vs Packing Superchannel Grooming; Deterministic vs Holing vs Packing Superchannel Release)

All the scenarios are coincident with respect to the blocking probability, thus illustrated with a single curve. Observing the other statistics (the corresponding graphs are not here reported), it is observed that the combination of the Superchannel Grooming and Superchannel Release policies does not affect the final performance of the network. The choice of the sole Superchannel Release induces a slight variation in the fragmentation ratio; the graph is reported in Figure 52 below. The different combinations of policies result in three different cases, depending on the Superchannel Release policy. The case that has highest f_{rat}, which represents the case with more fragmented spectrum, is the one exploiting Deterministic Superchannel Release, followed by the Holing case and, finally, the least fragmented with Packing Superchannel Release. The lines inside each case are undistinguishable. The difference among the three cases is minimum, indeed, the Y axis varies only between 0 and 0.1.

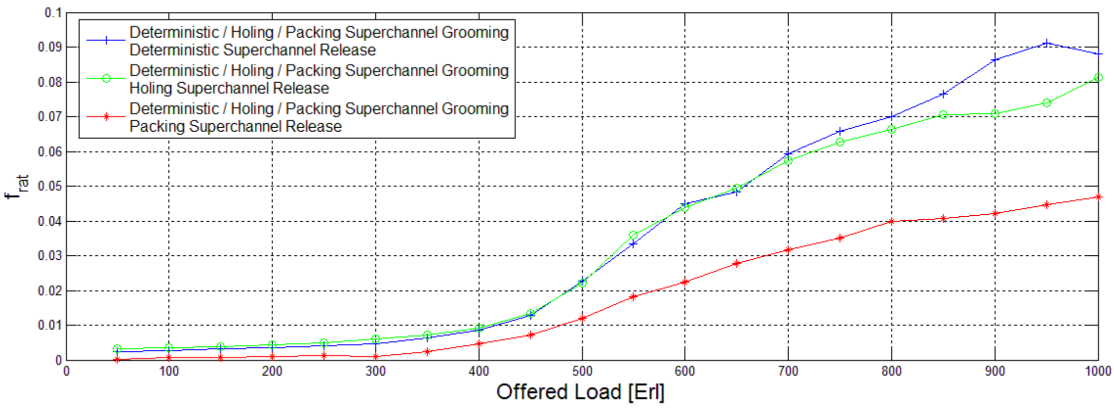

Figure 52. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assingment; Deterministic vs Holing vs Packing Superchannel Grooming; Deterministic vs Holing vs Packing Superchannel Release)

The same behavior is obtained for the other two scenarios, where the Spectrum Assignment policy is different. There are not noticeable differences in the blocking probability; so the two graphs are not here reported. However, we illustrate the obtained results for the fragmentation ratio both with the hypothesis of Random Spectrum Assignment (Figure 53) and under the assumption of the Spectrum Assignment parameter set to the Spread value (Figure 54). The available options group into three categories, each characterized by one Superchannel Release policy. The difference among the three groups are not remarkable.

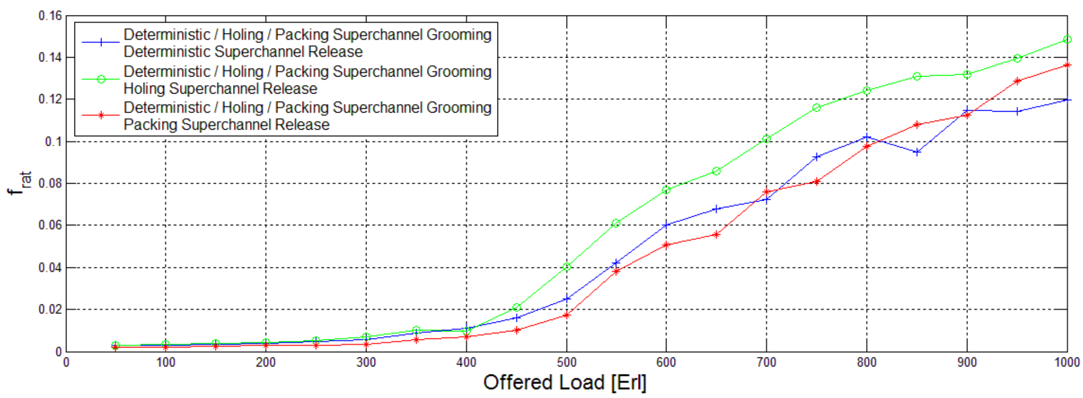

Figure 53. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Random Spectrum Assingment; Deterministic vs Holing vs Packing Superchannel Grooming; Deterministic vs Holing vs Packing Superchannel Release)

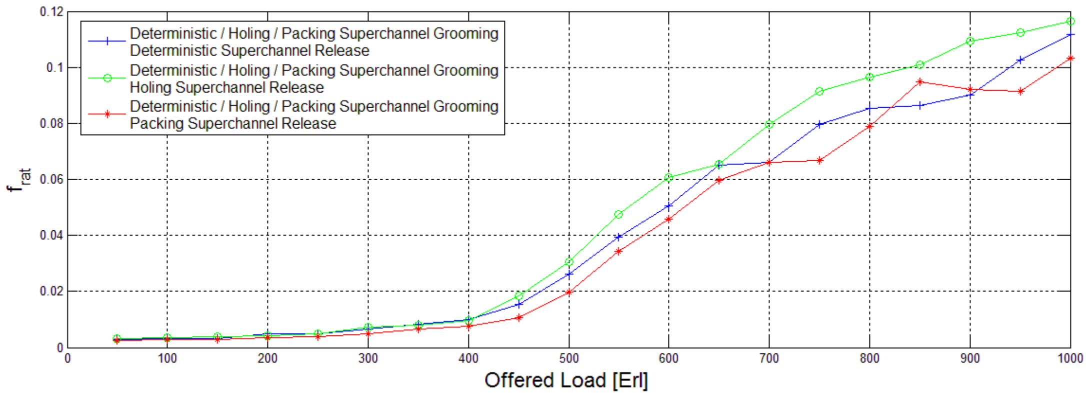

Figure 54. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Spread Spectrum Assingment; Deterministic vs Holing vs Packing Superchannel Grooming; Deterministic vs Holing vs Packing Superchannel Release)

After this analysis, we can assert the following: the combination of Superchannel Grooming and Superchannel Release policies does not affect the performance of the network significantly. The Superchannel Release slightly influences the fragmentation ratio, the packing option fragmenting less compared to the others, while such statistic is completely transparent to the Superchannel Grooming policy. It can be also observed that the combination of a certain policy for the Grooming with a different policy for the Release does not bring any particular advantage.

6.3 Impact of Spectrum Assignment

The impact of the Spectrum Assignment policy on the network performances is analyzed in this Section. Analogously to the previous Section, the analysis is carried out over more than a single scenario. Nominally, the combination of the Superchannel Grooming and Superchannel Release policies will vary in each scenario. Since we have showed in the previous Section that there is not a particular advantage in combining a specific Grooming policy with a different Release policy, the two policies will be considered equal and varying only from one scenario to the other.

We start analyzing, as usual, the blocking probability as summarizing statistic. In Figure 55 the p_{block} is shown for the first scenario, where the Superchannel

Grooming & Release policies are both accomplished with the Deterministic policy.

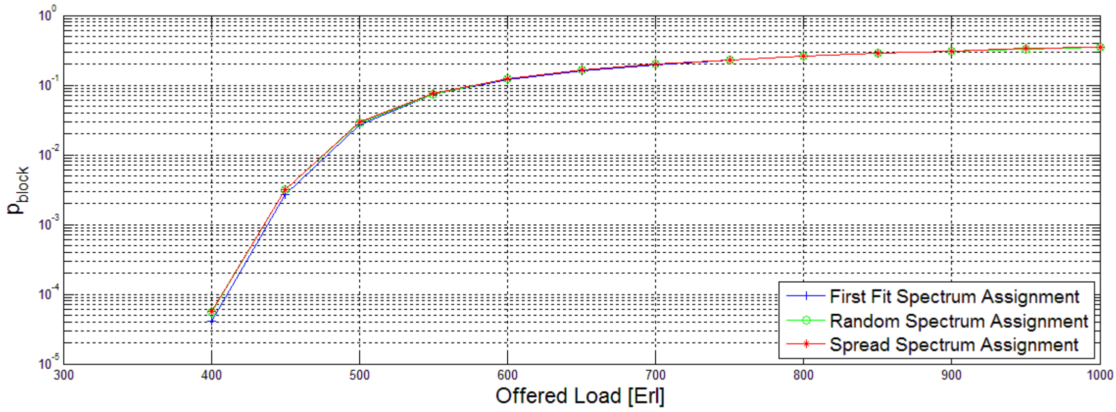

Figure 55. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Deterministic Superchannel Grooming & Release; First Fit vs Random vs Spread Spectrum Assignment)

It can be seen that the First Fit option (blue line) provides a small improvement in a situation of very low blocking probability. The other two lines are almost undistinguishable. The detail of the obtained results for scarcely loaded network are reported in Figure 56 below, where the improvement obtained in the First Fit Spectrum Assignment scenario is more visible.

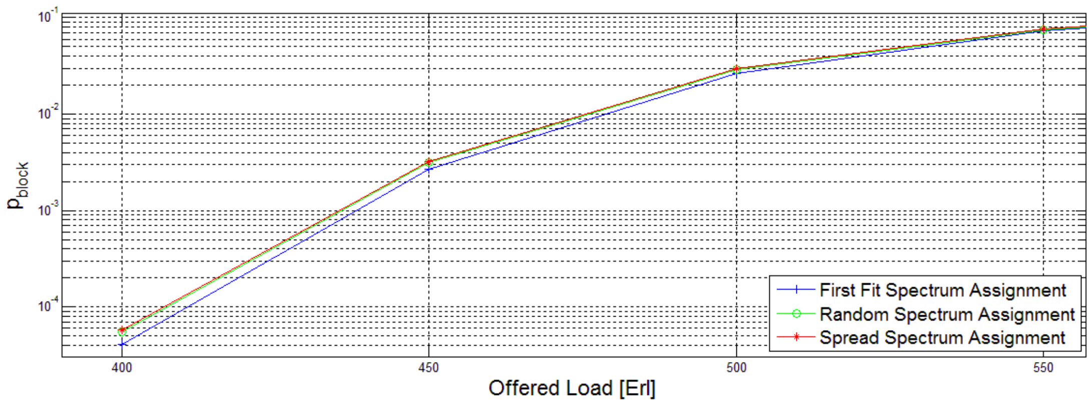

Figure 56. Detail of Fig. 54. Offered traffic varies from 400 to 550 Erl

The obtained result does not vary when, in the other scenario, another Superchannel Grooming & Release policy is chosen. The only exception is the fragmentation ratio. Here the three Spectrum Assignment options lead to different tendencies, as illustrated in Figure 57.

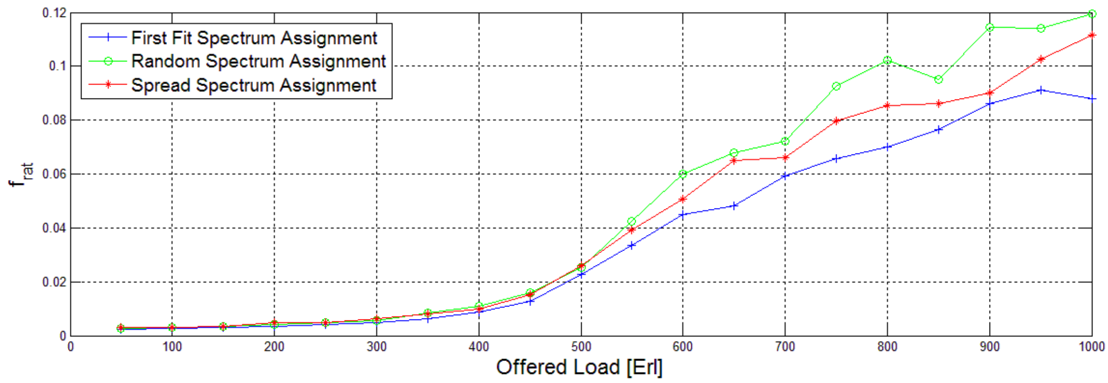

Figure 57. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Deterministic Superchannel Grooming & Release; First Fit vs Random vs Spread Spectrum Assignment)

As expected, the First Fit policy leads to a less fragmented spectrum. Unpredictably, the Random spectrum assignment fragments the spectrum more than the Spreading policy. A closer look to the lower values of Offered Load can help explaining such result. In Figure 58 below it is represented the detail of the obtained graph for Offered Load up to 400 Erl. The two lines referring to Random (green) and Spread (red) Spectrum Assignment are almost parallel, with the Spread always lying above the Random curve which means it fragments more. The two lines cross at around 350 Erl when the network starts to be significantly loaded . It is the fact that the random function disregards the possibility of future superchannel grooming that influences the fragmentation. In fact, Spread Spectrum Assignment fragments in order to give fair possibility to the newly installed frequency slot, as well to the first to its left and to its right, to be the frequency slot where to groom a future connection. On the other hand, Random fragments but acting in a random way thus disregarding what will come in a second time. The result is that, with Spread Spectrum Assignment, future connection requests are more likely to be accommodated by means of grooming, avoiding the establishment of a new frequency slot. Such event leads to a less fragmented spectrum and, in conclusion, provides the explanation of the result obtained in Figure 57.

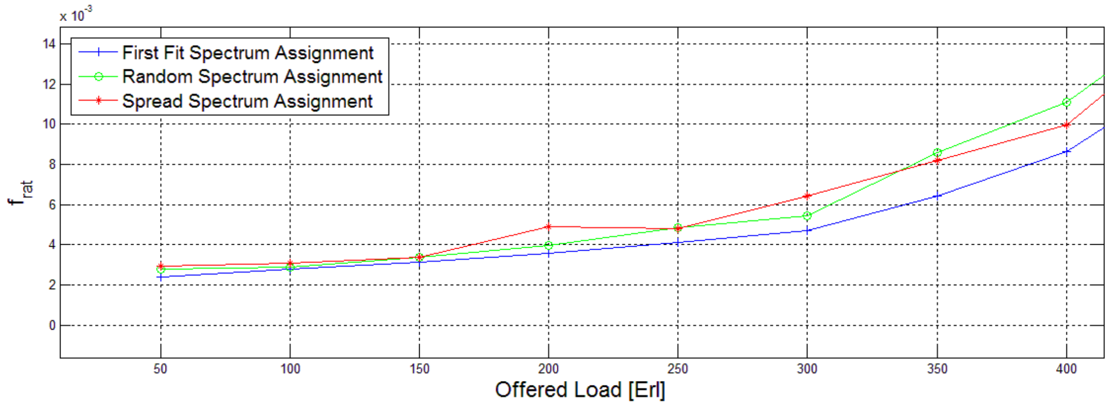

Figure 58. Detail of Fig. 56. Offered traffic varies from 50 to 400 Erl

We conclude the Section showing the results obtained for the other two scenarios, where the Superchannel Grooming and Superchannel Release are first accomplished with the Holing policy, then Packing. The performances in the two scenarios are completely similar to what shown in the first part of the Section. We show the fragmentation ratio curves in the Holing Superchannel Grooming & Release scenario in Figure 59, while the Packing Superchannel Grooming & Release policies in Figure 60. It can be noticed that the three tendencies, according to the spectrum assignment policy, are very similar to what shown in Figure 57 for the Deterministic scenario; the differences among the three lines are though more definite.

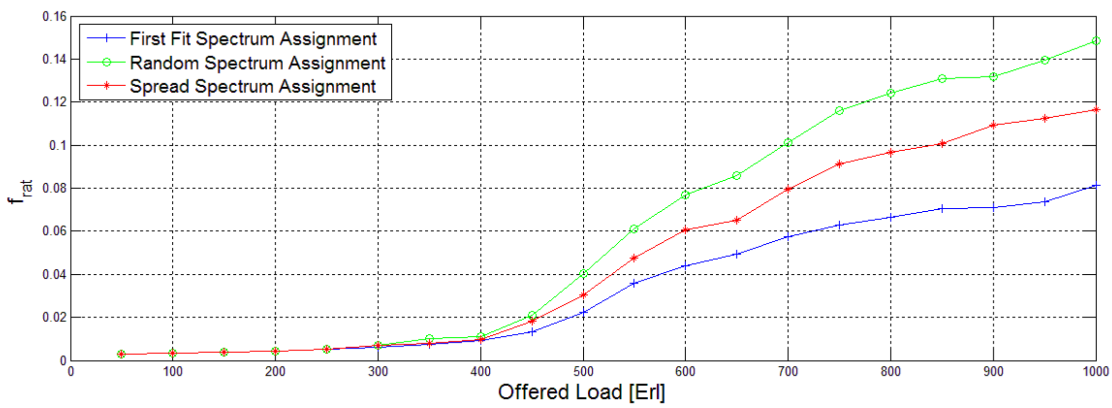

Figure 59. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Holing Superchannel Grooming & Release; First Fit vs Random vs Spread Spectrum Assignment)

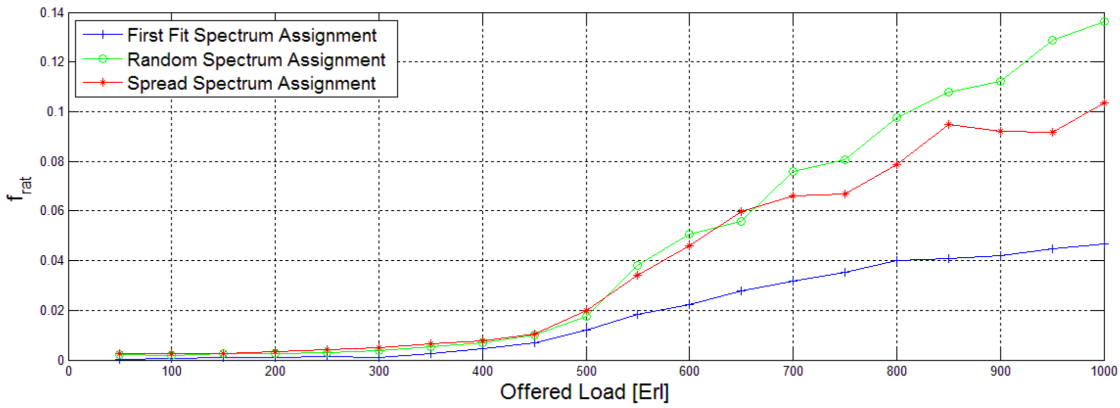

Figure 60. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Packing Superchannel Grooming & Release; First Fit vs Random vs Spread Spectrum Assignment)

6.4 Impact of Objective Function

We now analyze the effect over the network performance produced by the variation of the objective function parameters α and β.

As for the previous cases, we analyze more than a single scenario. Each scenario will be characterized by a different Spectrum Assignment policy. Moreover, the analysis will be carried out for each of the traffic distribution assumptions: uniform or not uniform. Hence, in total, six scenario. The Clcokwise vs Counterclockwise Tie Resolution is accomplished according to the Least Used Link policy in all cases.

In the results that we will show, the objective function which minimizes the spectrum occupation implies that the cost assignment weight α is set to 1.0 while the weight β, which takes into account the variation in transponder utilization, is set to 0.01. On the other hand, the objective function which aims to the minimization of the transponder utilization is obtained setting α equal to 0.01 and β equal to 1.

We start analyzing the results obtained for the first scenario: the traffic is uniformly distributed and the Spectrum Assignment operating according to the First Fit policy. In Figure 61 it is shown how the change in objective function impact on the blocking probability. The change in the Superchannel Grooming &

Release parameters do not affect the performance, coherently with what stated in Section 6.2. Two well-defined tendencies are present: one for the minimization of the utilized transponders, and one for the objective function aiming to the minimization of the spectrum occupation. The latter performs better for low values of Offered Load (up to ca. 600 Erl), where the blocking probability is more than two orders of magnitude lower. For an offered load of 400 Erl, the spectrum- minimizing solutions present a blocking probability of $\sim 4 * 10^{-5}$, whilst the transponder minimizing ones shows $p_{block} \cong 2 * 10^{-2}$.

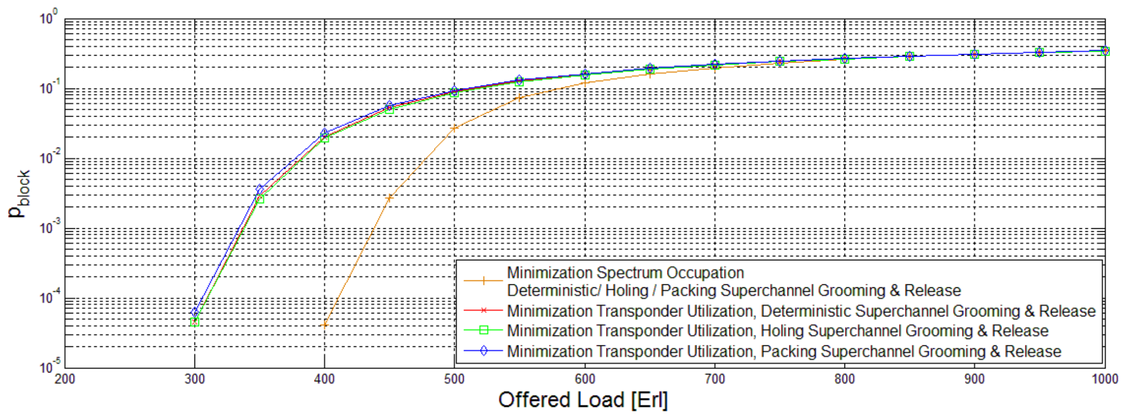

Figure 61. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

The explanation of this result can be easily explained with Figure 62 and Figure 63. The objective function focuses on minimizing the number of utilized transponder and disregards the spectrum, an inefficient usage of the available bandwidth is done (Figure 62) and the frequency slots are more sparsely allocated, causing a fragmented spectrum (Figure 63). The high fragmentation ratio is thus the cause of why the two groups of lines relative to the bandwidth utilization in Figure 62 crosses: the spectrum is fragmented, so the available portions of optical bandwidth are not able to accommodate large frequency slots.

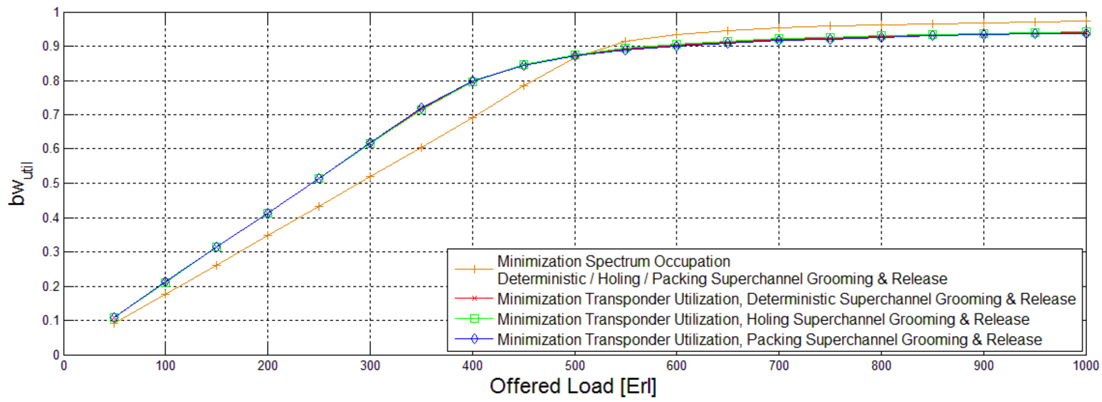

Figure 62. Bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

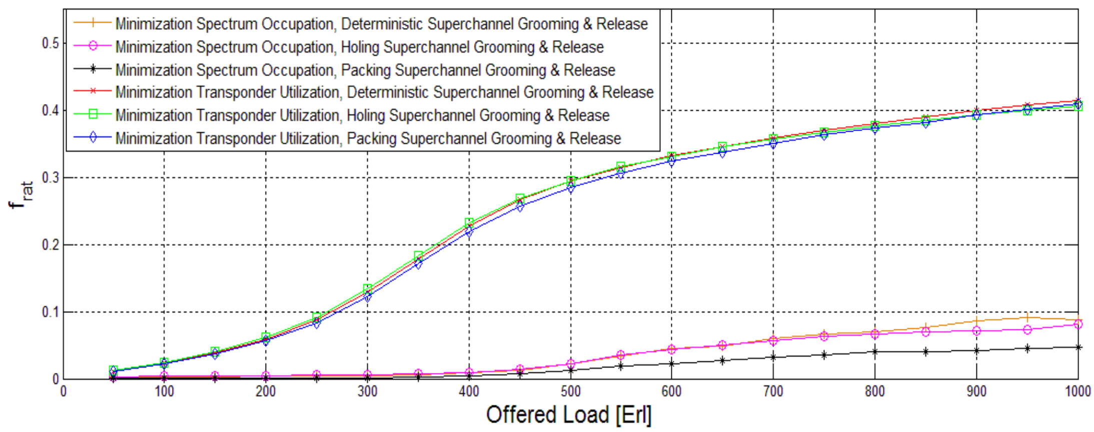

Figure 63. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

Thus an inefficient usage of the available bandwidth is obtained, in this flexible scenario, due to a low exploitation of the grooming capability. This is confirmed by Figure 64 below, where the relative guardband bandwidth utilization is given. The lower group of lines are those relative to the minimization of the spectrum occupation; they collapse in a single line. The three lines above express on the other hand a much higher impact of guardbands upon the totality of utilized spectrum. As previously said, this is given by the presence of a plurality of small frequency slots rather than less, but wider, frequency slots.

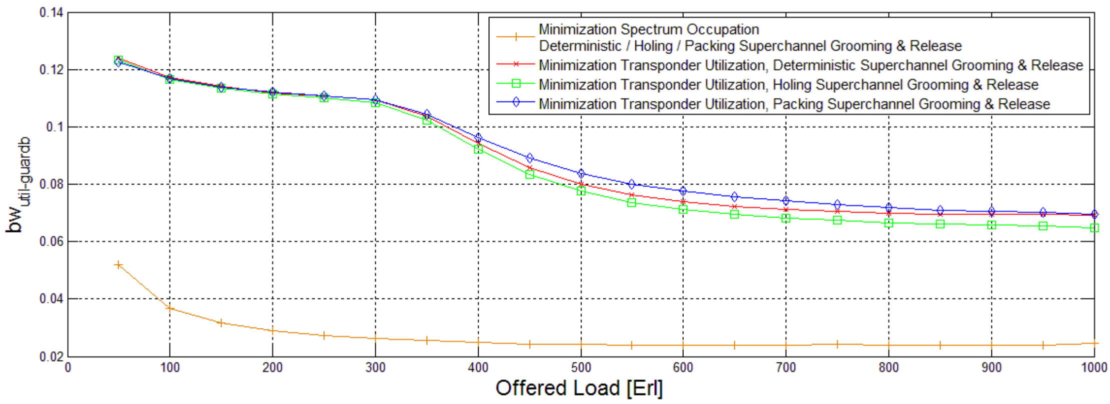

Figure 64. Relative guardband bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

We can conclude the analysis observing that the change of objective function actually impact on the number of utilized transponders. The obtained results for the $\overline{trx}$ statistic are illustrated in Figure 65. The savings in number of such resources can be diversified in three separate phase. In a first phase (up to an offered load of 300 Erl), a minimization of the utilized transponders implies a sparing of ca. 50 % of the resources when compared with minimization of spectrum occupation. At 300 Erl the first connection losses occur when aiming to minimize the utilized transponder; it can be seen from the p_{block} graph. The minimization thus do not work as efficiently as before from this point on; in this second phase, it has to give some way to the utilization of extra transponders in order to make up for the inefficiency in the spectrum utilization adopted so far. This second phase is characterized by a steeper pendency for the increase of the utilized transponders and a reduction in the gap with respect to the other objective function. In a third phase the pendency of the increase is reduced till reaching the final flat behavior. The gap with the group of lines which aim to minimize the spectrum occupation is constant in this phase. The reason why the spectrum minimization lies above the transponder minimization, even if the blocking probability is equal, is that a more efficient utilization of the available optical bandwidth in the previous two phases allows to have more frequency slots allocated. We can support this explanation observing that the gap in the number of utilized transceivers is remarkably higher, ca. 500, and it is not fully explainable only with the slightly higher bandwidth utilization (Figure 62). This discrepancy in the two graph thus finds its answer in the fragmented (i.e. inefficiently used) spectrum.

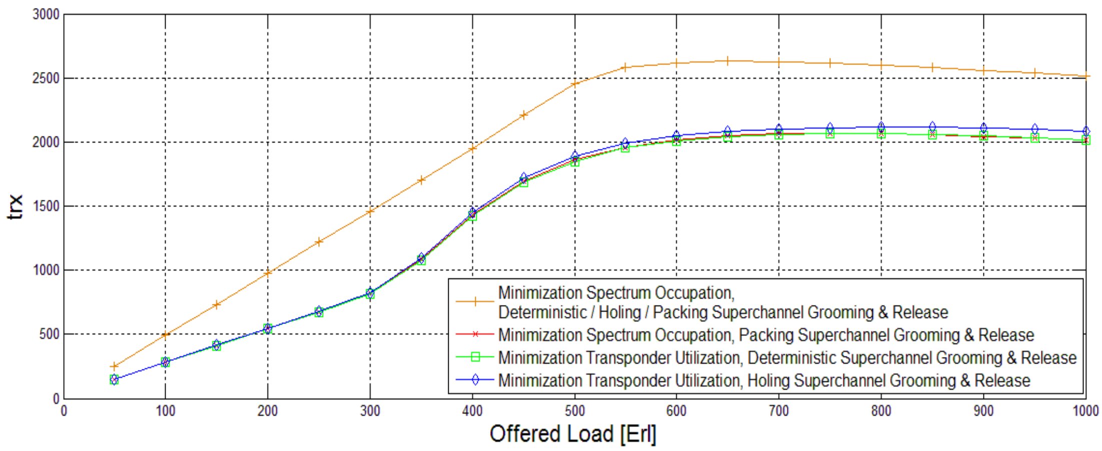

Figure 65. Average number of utilized transponders for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

The detailed analysis carried out on this first scenario is also valid for the remaining scenarios. For the sake of completion we report in the remaining part of the Section the obtained results for the sole statistics p_{block}, f_{rat} and $\overline{trx}$.

In Figure 66 the p_{block} statistic obtained under the hypotheses of uniform Traffic Distribution and random Spectrum Assignment is shown. In Figure 67 we show the fragmentation ratio and in Figure 68 we plot the number of utilized transceivers. The same hypotheses are still assumed in these two graphs.

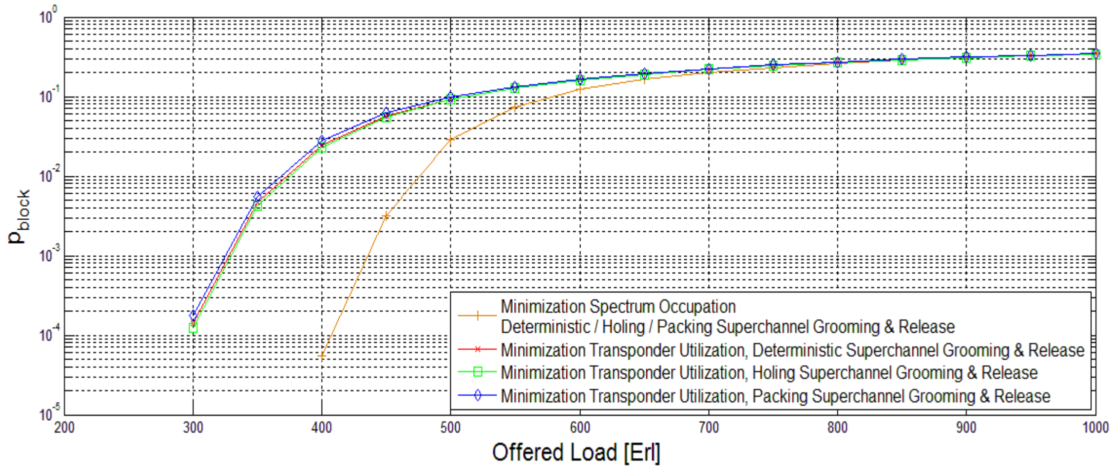

Figure 66. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

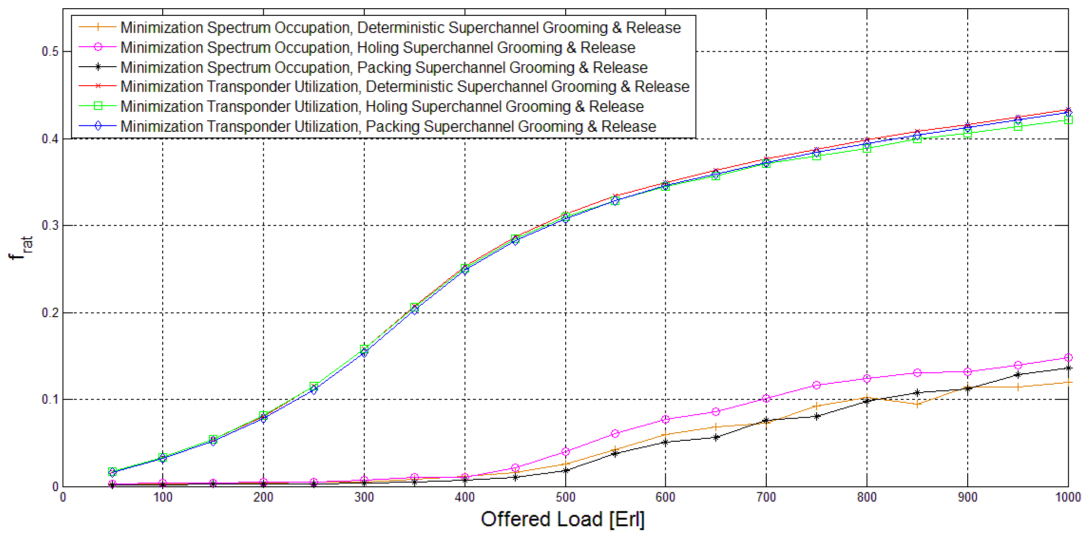

Figure 67. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

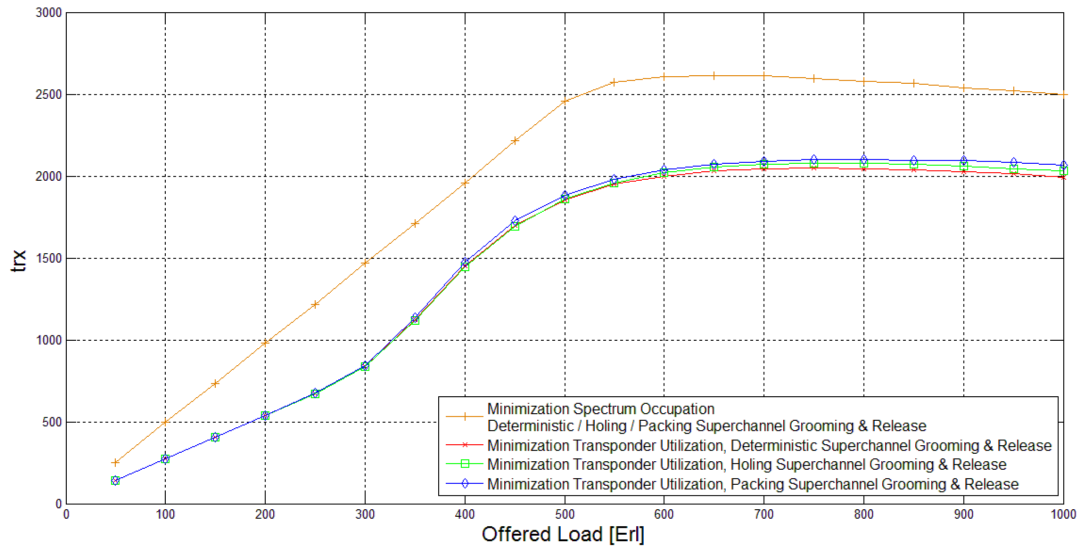

Figure 68. Average number of utilized transponders for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

In the next graphs we show the results obtained under the assumption of uniform Traffic Distribution and Spread Spectrum Assignment policy. In Figure 69 the blocking probability p_{block} is shown, in Figure 70 we plot the fragmentation ratio f_{rat} and, finally, in Figure 71 the average number of utilized transponders $\overline{trx}$ is reported.

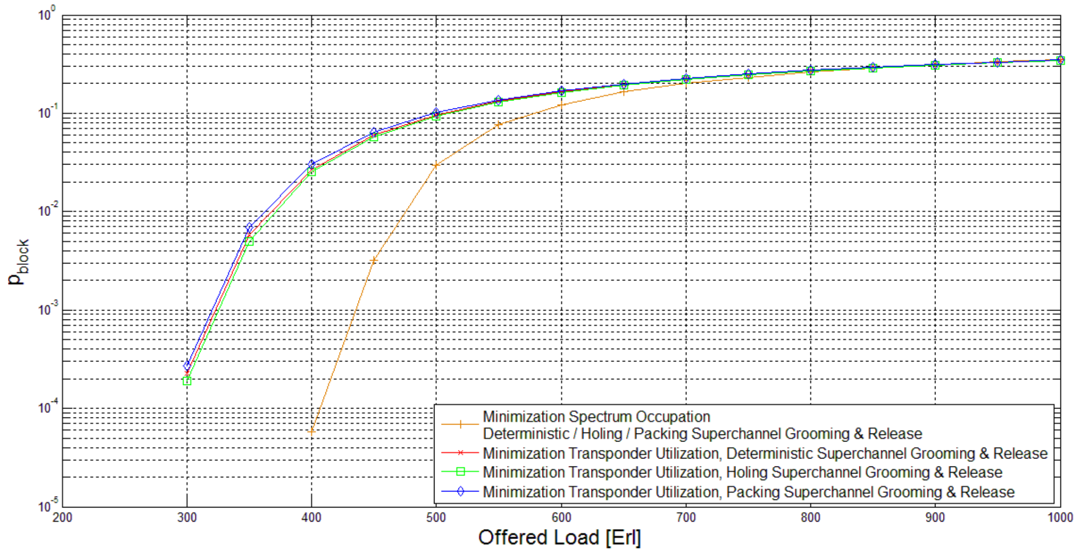

Figure 69. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Spread Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

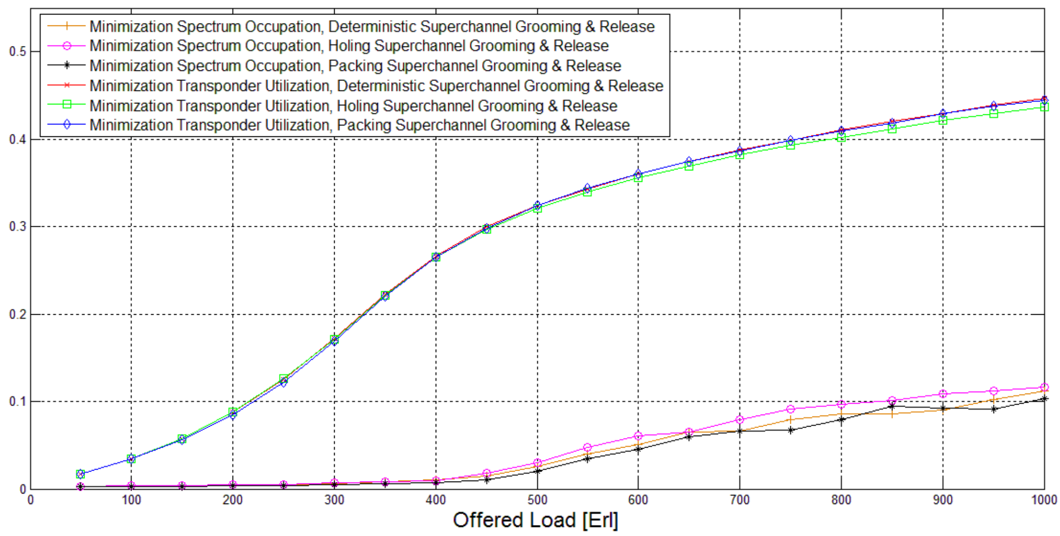

Figure 70. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Spread Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

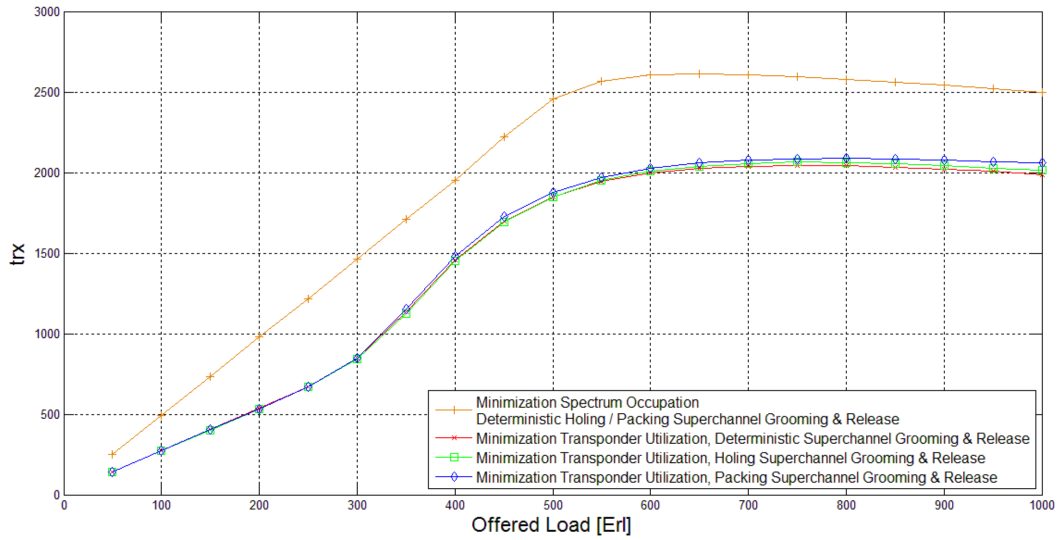

Figure 71. Average number of utilized transponders for the metro network in relation to the offered load (Uniform Traffic Distribution; Least Used Link Tie Resolution; Spread Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

We thus reply these scenarios but changing the Traffic Distribution parameter to not uniformly distributed traffic. In case of First Fit Spectrum Assignment, in the following graphs the obtained results are illustrated with regard to the blocking probability p_{block} (Figure 72), the fragmentation ratio f_{rat} (Figure 73) and the average number of utilized transponders $\overline{trx}$ (Figure 74).

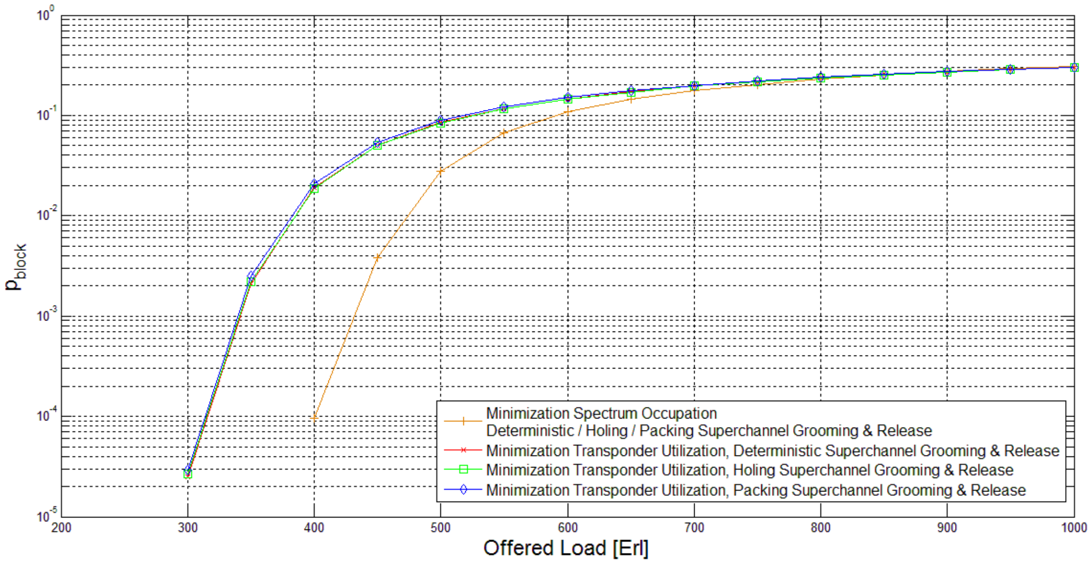

Figure 72. Blocking probability for the metro network in relation to the offered load (Not Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

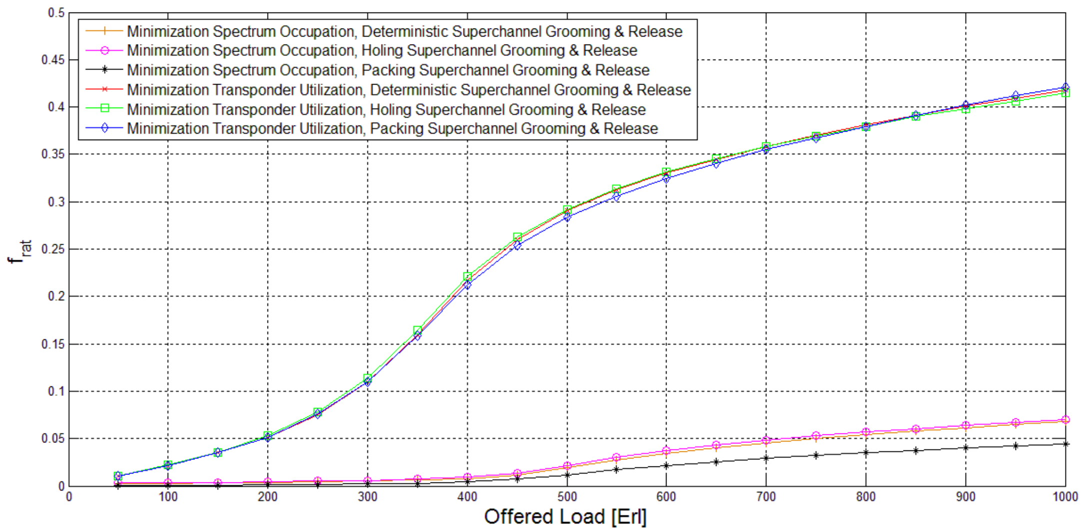

Figure 73. Fragmentation ratio for the metro network in relation to the offered load (Not Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

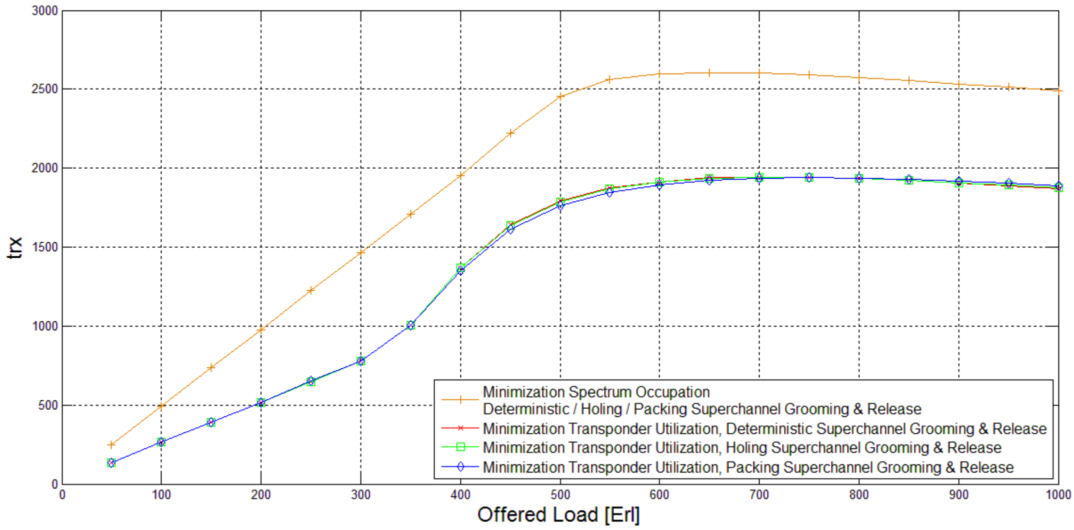

Figure 74. Average number of utilized transponders for the metro network in relation to the offered load (Not Uniform Traffic Distribution; Least Used Link Tie Resolution; First Fit Spectrum Assignment; spectrum vs transponder minimization; Deterministic vs Holing vs Packing Superchannel Grooming & Release)

As it can be observed by comparing these graphs with the first analyzed scenario (from Figure 61 to Figure 71), also the change in traffic distribution does affect the results significantly. Minor variations in the observed values can be measured, but the tendencies and the observation deduced so far are still valid. Hence we do not report the obtained graphs.

7 Routing, Modulation Level and Spectrum Assignment (RMLSA) Algorithm

In Chapter 5 and Chapter 6 all the performance analyses have been carried out under the assumption that the transceivers adopt a unique modulation format (assumption A.11), nominally the dual-polarization quadrature phase-shift keying (DP-QPSK). As previously stated, in the last part of this work such assumption will decay. In fact, in this Chapter we are going to analyze the effect of adding the Multiple Modulation Format (MMF) feature to the transceivers.

The possibility of exploiting MMF allows to use a certain modulation format according to the distance that the optical path have to cover before being regenerated. This flexibility in choosing the constellation diagram allows to use modulation formats with higher spectral efficiency if the distance is short as well as to reduce the number of bits per symbol in order to cover longer distances without the need of OEO (optical-electronic-optical) regeneration. We have dealt with the MMF capability in Section 3.3 .

In the first Section we show some results obtained by means of an Integer Linear Programming (ILP) formulation. In this model, a fixed set of static connection requests is given as input of the problem. The Second section describes the results obtained by an adaptation of the RSA dynamic algorithm adopted so far. The new algorithm will be named Routing, Modulation Level and Spectrum Assignment (RMLSA) Algorithm.

7.1 Results from ILP model

To the best of our knowledge, in literature there are no previous works which deal with a greedy algorithm for routing, modulation level and spectrum assignment in flexible ring metro networks. Nevertheless, it is worth mentioning the paper “On the benefits of Elastic Transponders in Optical Metro Networks”

[75], where it is formalized an ILP model of a metro network where the transceivers can exploit a flexible grid with multiple modulation format. A few differences have to be pointed out when comparing with what we have assumed so far:

- The minimum optical spectrum granularity (i.e., the spectrum slice width) allowed is 5-GHz wide
- An optical reach of 3000 km for the BPSK modulation format is assumed, higher modulation formats follow the simplified formula where the increase of the modulation format of 1 bit per symbol implies the transmission distance halves.
- The transponders can vary their optical width from 5 GHz to a maximum of 100 GHz by 5-GHz wide steps. When more than one transponder is needed to carry the required traffic, a guardband of 5 GHz (thus as wide as the bilateral guardbands) is necessary between the adjacent transponders.
- The analysis is carried out on a metro ring network made of eight nodes

Pointed out these differences with regard to the analyzed scenario, we can observe the obtained results. In Figure 75 the obtained savings in spectrum occupation are illustrated, in relation with the traffic capacity required between a pair of nodes, with respect to the classic WDM approach. The traffic on the x-axis is assumed to be required from each node to any other node belonging to the ring. The WDM ring adopts as unique constellation diagram the PDM-DQPSK modulation with spectral efficiency equal to 2 (i.e. 100 Gbit/s over a 50 GHz optical spectrum spacing). Three different scenarios are considered, where the radius R of the ring changes. Varying the radius, the transmission distance from node to node increases and as a consequence the used modulation format tends to decrease.

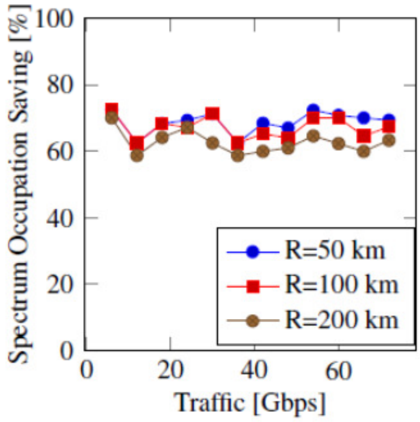

Figure 75. Spectrum savings (in percentage) of elastic vs fixed metro networks (network radius equal 50, 100 or 200 km)

It is evident from the obtained that the exploitation of “elastic” transponders in metro networks results in remarkable gains: spectrum occupation savings vary between 60% and 80%. These figures gives an idea of the potential savings involved in combining the two technologies, flexible grid and Multiple Modulation Format, especially into metro networks, where the distances to be covered vary from few tens to few hundreds of kilometers.

7.2 RMLSA algorithm for dynamic traffic

In this Section we add the MMF capability to the RSA algorithm described in Chapter 4. Thus, in addition to Spectrum and Routing Assignment, also the Modulation Level of each lightpath is a decision variable. Whilst in Chapter 5 and Chapter 6 a univocal correlation between required bandwidth and required spectrum (i.e. required number of spectrum slices) was possible, such correlation is now function of the transmission distance between source and destination nodes.

The algorithm always adopts the highest possible modulation format for the optical reach to cover. Thus the modulation format is set according to the distance between source and destination nodes. The allowed modulation formats are 8-QAM, 16-QAM, 32-QAM and 64-QAM, transmitting 3, 4, 5 and 6 bits per symbol, respectively. For the maximum transmission distance that each modulation format can cover, we refer the reader to Table 13 presented in Subsection 3.5.3 .

A network radius r_{ring} equal to 50km is assumed, as for the RSA algorithm in Chapters 5 and 6. The nodes are assumed equally distant. With a network radius equals to 50 km, the circumference c_{ring} is about 314 km, then each link is about 52 km long. The adopted modulation formats, with respect to the number of hops to cover in order to transmit from source node s to destination node d, are summarized in Table 16. As we are considering a ring network made up of 6 nodes (assumption A.4), the maximum number of hops to go from s to d is 5.

Number of hops	Transmission distance [km]	Modulation format
1	52	64-QAM
2	104	64-QAM
3	156	32-QAM
4	208	32-QAM
5	260	32-QAM

Table 16. Adopted modulation format in relation to the number of hops in a ring network with radius equal to 50 km

Both Traffic Distribution policies will be considered: Uniform and Not Uniform. The two distributions will be applied, in turn, to two different scenarios: a first scenario characterized by an objective function which minimizes the spectrum occupation, and a second scenario aiming to the minimization of the utilized transponders. The rest of the policies to provide to the algorithm as input, in both scenarios, will be fixed: the network is grooming-capable, when a Clockwise vs Counterclockwise Tie Resolution occurs the Least Used Link policy is adopted, the spectrum is assigned according to the Random scheme and, finally, both Superchannel Grooming and Superchannel Release follow the Holing policy.

We first analyze in Subsection 7.2.1 the scenario where we minimize the spectrum occupation and the traffic is uniformly distributed. The scenario with transponder minimization and uniform traffic distribution is dealt with in

Subsection 7.2.2 . The scenarios with not uniform traffic distribution are illustrated in Subsection 7.2.3 .

7.2.1 RMLSA with Occupied Spectrum Minimization (Uniform Traffic Distribution)

The first scenario we analyze is the one characterized by an incoming traffic uniformly distributed and an objective function which aims to minimize the spectrum occupation. The obtained blocking probability is illustrated in Figure 76.

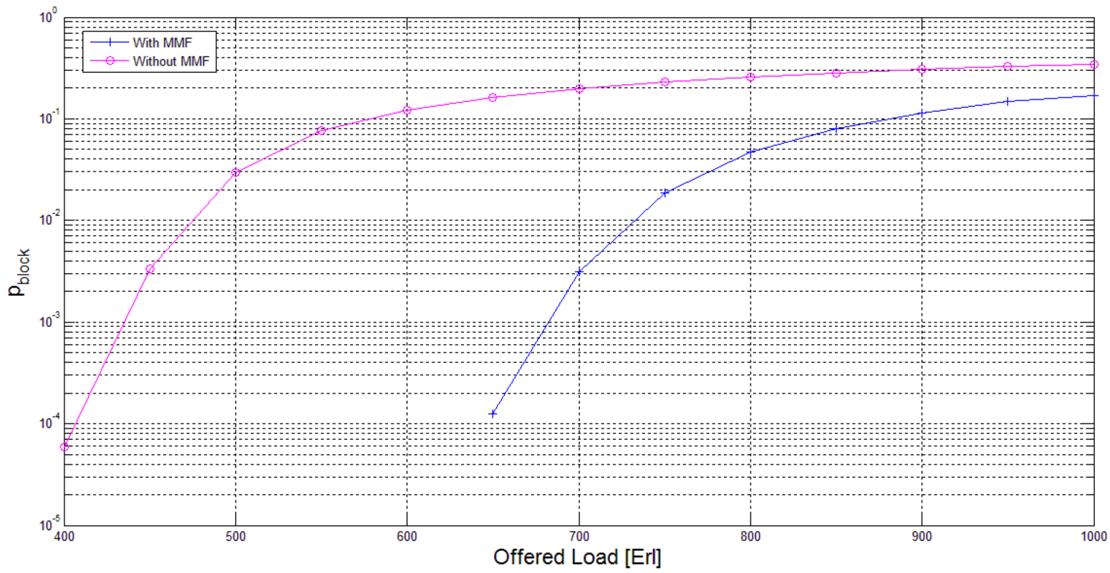

Figure 76. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

The improvements brought by the introduction of the MMF are remarkable. The network saturates its resources at higher loads than the case where no MMF is allowed. For a fixed offered load the blocking probability if exploiting the MMF capability is up to several orders of magnitude lower. For instance, if we consider an offered load of 650 Erl, the introduction of the MMF capability leads to a blocking probability three orders of magnitude lower.

It is possible to motivate the obtained result analyzing the bandwidth utilization first. The behaviour of the bw_{util} statistic is illustrated in Figure 77.

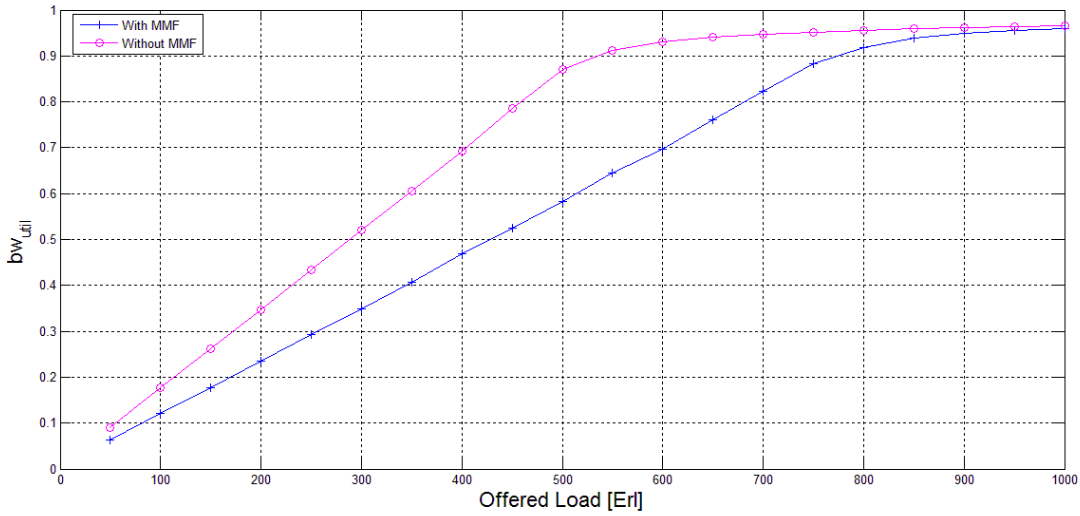

Figure 77. Bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

The possibility of exploiting denser constellations for modulating the signal, hence higher spectral efficiency, in case of short transmission distance, translates into the possibility of accommodating higher amounts of traffic over the same portion of optical bandwidth. Consequently, the spectrum occupation reduces, as shown in Figure 77 above.

In the two cases, the bandwidth utilization increases with constant gradient, before starting to assume a flat increment. The line representing the scenario with MMF (blue line) has a less steep gradient if compared with the solution which adopts fixed modulation format (purple line). Moreover, the linear increase is maintained up to higher loads in the MMF scenario, till the offered load is equal to 750 Erl, whereas in the fixed modulation format scenario the utilized spectrum increases linearly till the offered load is equal to 500 Erl. This means that the network starts to experience saturation on its links at higher traffic loads.

Another confirmation of the different dynamics of the MMF and fixed modulation format cases is given by the statics bw_{util_guardb} and f_{rat}. Their graphs are illustrated in Figure 78 and Figure 79, respectively.

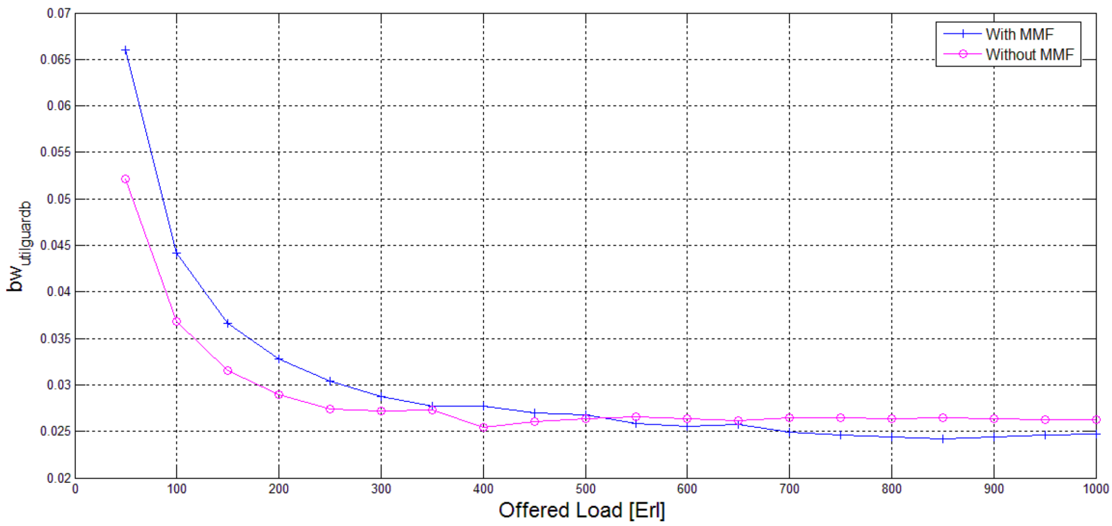

Figure 78. Relative guardband bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

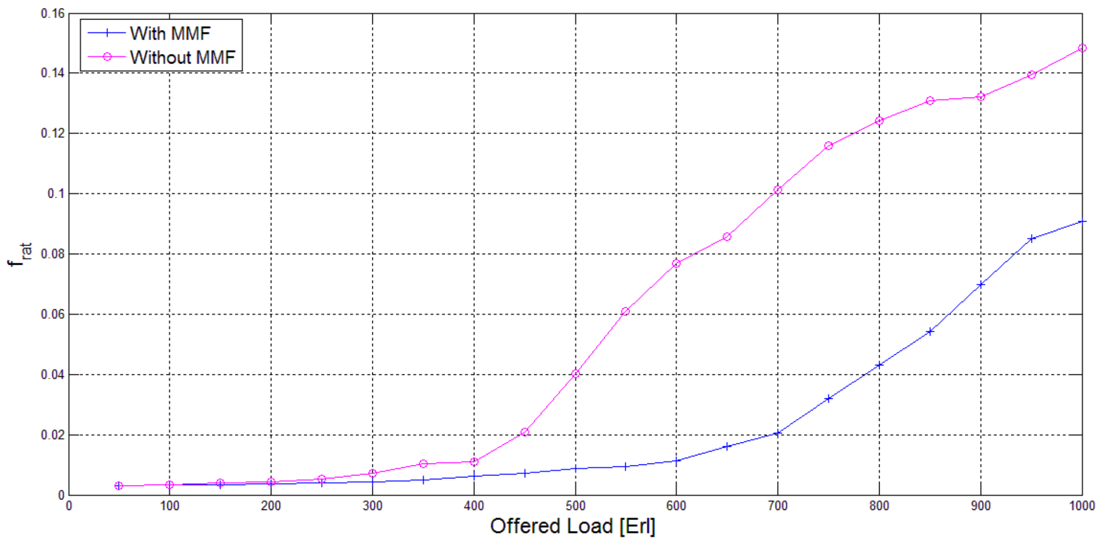

Figure 79. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

Figure 78 confirms that, with the MMF capability, given a fixed optical spectrum width, larger amounts of electronic traffic demands are allocated. In the MMF scenario the frequency slots are smaller, so the impact of guardbands over the total utilized spectrum is bigger.

In Figure 79 it is shown that the fragmentation ratio, for very low values of offered loads, is roughly the same in the two scenarios. When the network is lightly loaded, different sizes of the frequency slot do not necessarily imply changes in the fragmentation.

Then it can be observed that, in both cases, when the network starts to not be able to accommodate all connection requests, the fragmentation ratio starts increasing more steeply and the impact of guardbands on the total utilized spectrum assumes a flat tendency. This "threshold" for the MMF scenario and the fixed modulation format scenario can be identified around offered load equal to 400 Erl and 650 Erl, respectively. We can observe in Figure 77 that such values of offered load, in each of the two scenarios, are the values at which the blocking probability is for the first time not null. Thus we can state that for these values of average offered load the network starts to experience saturation on its links.

Finally, still from Figure 78 and Figure 79 we can observe that, for high offered loads (right hand part of the two graphs), the MMF scenario presents lower bw_{util_guardb} and less fragmented spectrum. This can be attributed to the fact that in the MMF the spectrum occupation increases in smaller portions; hence superchannel grooming and spectrum assignment are carried out in a more efficient way. When the links, or some of them, starts to be fully loaded, the optimal solution is not always available. In fact, the optimal solution tends to widen an already existing frequency slot in order to groom the incoming connection request. Thus the connection is setup, when possible, in a not efficient way; for instance, a new frequency slot is installed, in the shortest path direction or, even worse, in the opposite direction. This induces higher fragmentation ratio and higher impact of the guardbands on the total utilized spectrum. In the MMF scenario, the bandwidth utilization is lower; the saturation of links takes place at higher values of offered loads. The efficient accommodation of the connection requests occurs for a wider span of values of offered load. Thanks to this efficient built up of the electronic traffic demands over the links in the MMF scenario, in the right-hand part of Figure 78, which refers to high values of offered load, the statistics bw_{util_guardb} suggests that more superchannels are present for equal total utilized spectrum (Figure 77 referring to bw_{util}). Hence the lower blocking probability for the MMF scenario (Figure 76 referring to p_{block}) comes as a direct consequence.

We conclude the analysis of this scenario, characterized by uniformly distributed traffic and objective function aiming to the minimization of the spectrum occupation, by analyzing the $\overline{trnx}$ statistic. Its graph is reported in Figure 80.

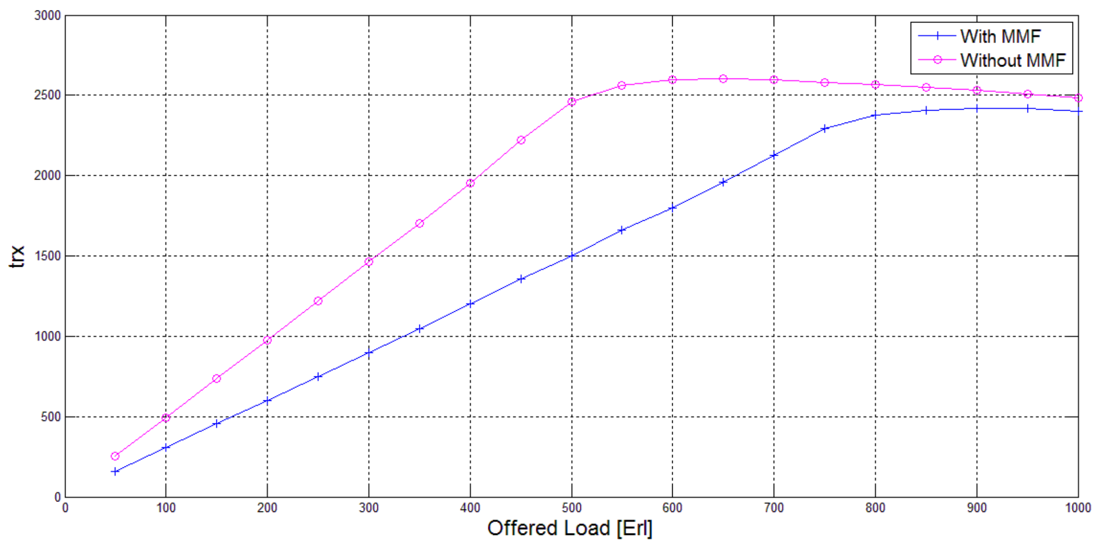

Figure 80. Average number of utilized transponders for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

As it could be expected, the number of utilized transponders is considerably lower when using MMF. Exploitation of high spectral efficiency for short transmission distances translates into the possibility of transmitting more data (i.e. higher amount of electronic traffic demands) with a single transceiver.

7.2.2 RMLSA with Transponder Minimization (Uniform Traffic Distribution)

We can now move the spotlight upon the second scenario, where the traffic is still uniformly-distributed but, differently from the previous one, the objective function aims to the minimization of the utilized transponders.

As it can be seen from the graph reported in Figure 81 below, the benefits brought by the MMF in terms of blocking probability are still significant (up to more than two orders of magnitude). The difference between the two lines is though less remarked if compared with the scenario where spectrum occupation is minimized.

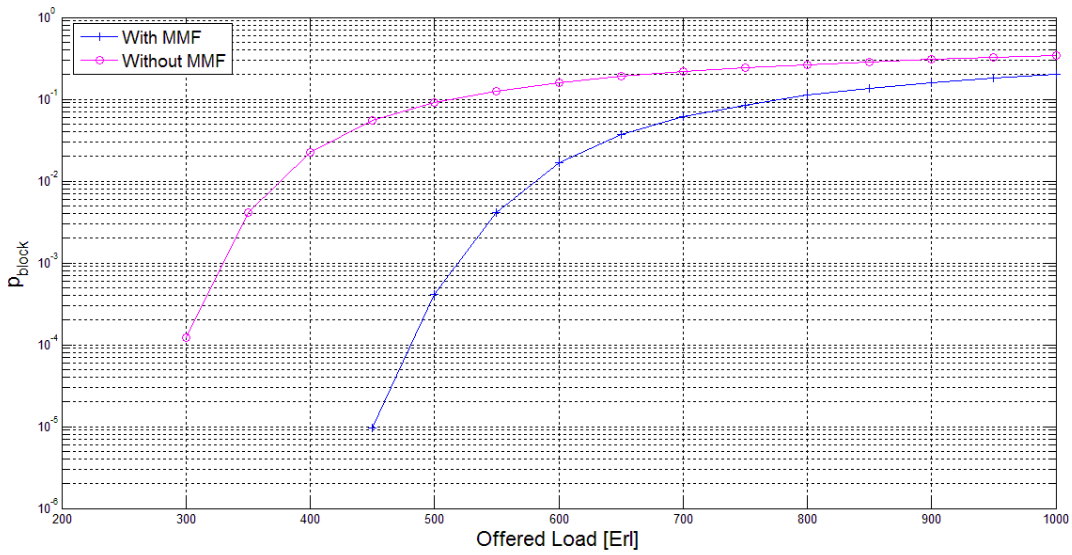

Figure 81. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; transponder minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

The other statistics follow the same pattern of the previous scenario. It is worth to report the obtained results for the fragmentation ratio f_{rat}; its graph is reported in Figure 82.

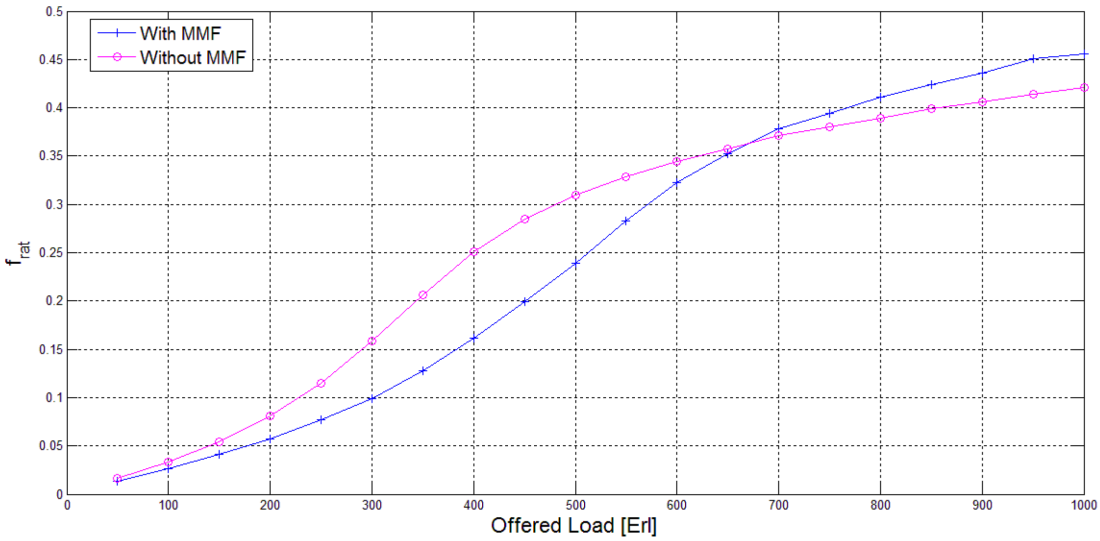

Figure 82. Fragmentation ratio for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; transponder minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

It can be noticed that, differently from the scenario of Subsection 7.2.1, the two curves cross and the network exploiting MMF, for higher loads, has a more fragmented spectrum. Let us remember that, since the objective function disregards the spectrum occupation, the connection requests are allocated in an inefficient way from the point of view of the optical bandwidth. This translates into high fragmentation ratio, both for the fixed modulation format and the MMF scenarios. With the spectrum irregularly allocated, new connection requests are likely to be dropped even if the resources are not fully allocated. In both scenarios, when the links start to saturate, the connection requests begin to be established along the only available routing option, which might be not optimal from the point of view of transponders utilization. It is clear that, in the MMF scenario, not optimal routing options means more installed transponders, hence shorter transmission distance, hence higher amounts of electronic traffic demands over the same portion of spectrum. Therefore, spectrum optimization is implicitly applied. As a result, the MMF network is able to allocate more traffic demands at the cost of increasing the fragmentation ratio.

This interpretation of the statistic f_{rat} is also confirmed by the statistic bw_{util_guardb}. The corresponding graph is reported in Figure 83. It can be observed how, differently from before, the MMF scenario lies above the single modulation format scenario also in the right-hand part of the graph. The purple line has an almost flat behaviour for a wide range of offered loads. The blue line is still decreasing in a significant way since for higher loads the MMF scenario keeps allocating connection requests and, implicitly, exploits short transmission distances and high spectral-efficient modulation formats.

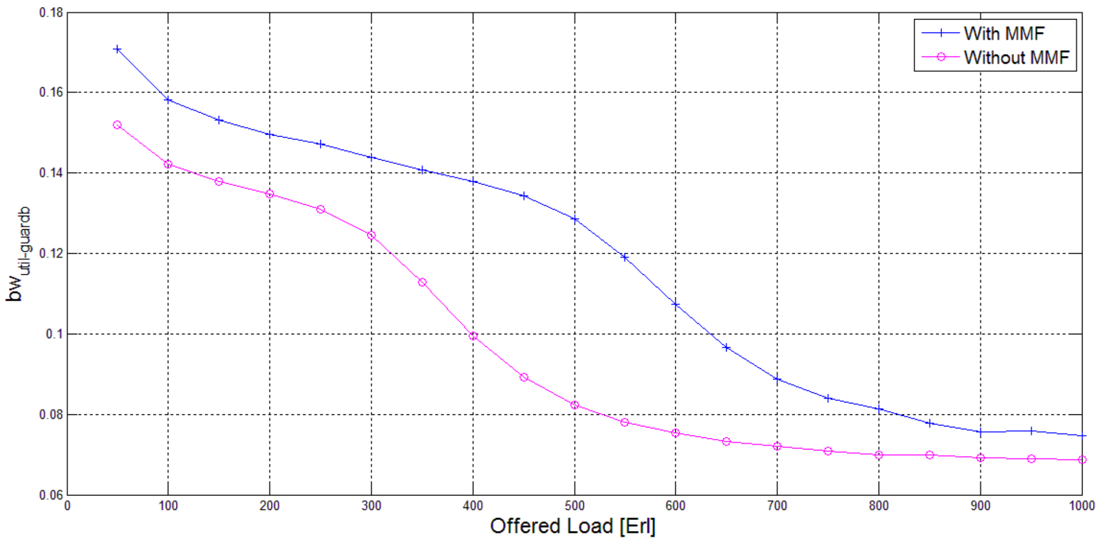

Figure 83. Relative guardband bandwidth utilization for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; transponder minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

We conclude the analysis of this scenario by reporting the obtained average number of utilized transponders. The graph of this statistic is reported in Figure 84.

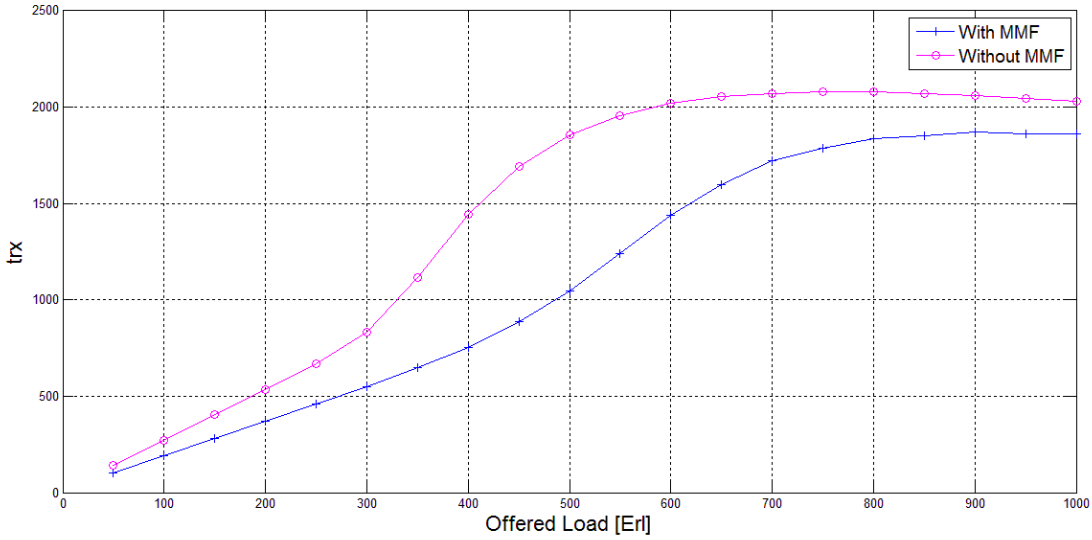

Figure 84. Average number of utilized transponders for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; transponder minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

As it could be expected, the number of utilized transponders is considerably lower if compared with the equivalent case of the previous scenario (blue line in Figure 80 for the MMF case, purple line still in Figure 80 for the fixed modulation format). The minimization of their usage is here the objective function. Nevertheless, the tendencies of the two graphs are analogous. First the two curves increase linearly, the gradient of the fixed modulation format being higher. Then it follows a phase where the increase is steeper; this phase starts for lower values of offered load in the fixed modulation format scenario and its change in gradient is more marked. Thus, in this phase it can be observed the gap between the $\overline{trnx}$ of the fixed modulation format and the $\overline{trnx}$ of the MMF increases. Finally it follows a phase of flat increase, reached by the fixed modulation format first. The gap between the two lines then wears thinner as traffic increases.

7.2.3 RMLSA for Not Uniform Traffic Distribution

With regard to the remaining two scenarios, both characterized by a not uniform traffic distribution while the objective function aims to minimize either the spectrum occupation or the traffic utilization, the obtained results are similar to the ones just shown. There are some slight differences in the obtained exact values, but the tendencies of the resulting graphs are equivalent to those just shown under the assumption of traffic uniformly distributed. For the sake of completion, we report in Figure 85 the blocking probability obtained for the scenario with traffic not uniformly distributed and the minimization of the spectrum occupation as objective function. In Figure 86 it is illustrated the obtained blocking probability for the MMF scenario with not uniform traffic distribution and the objective function which aims to minimize the utilized transceivers.

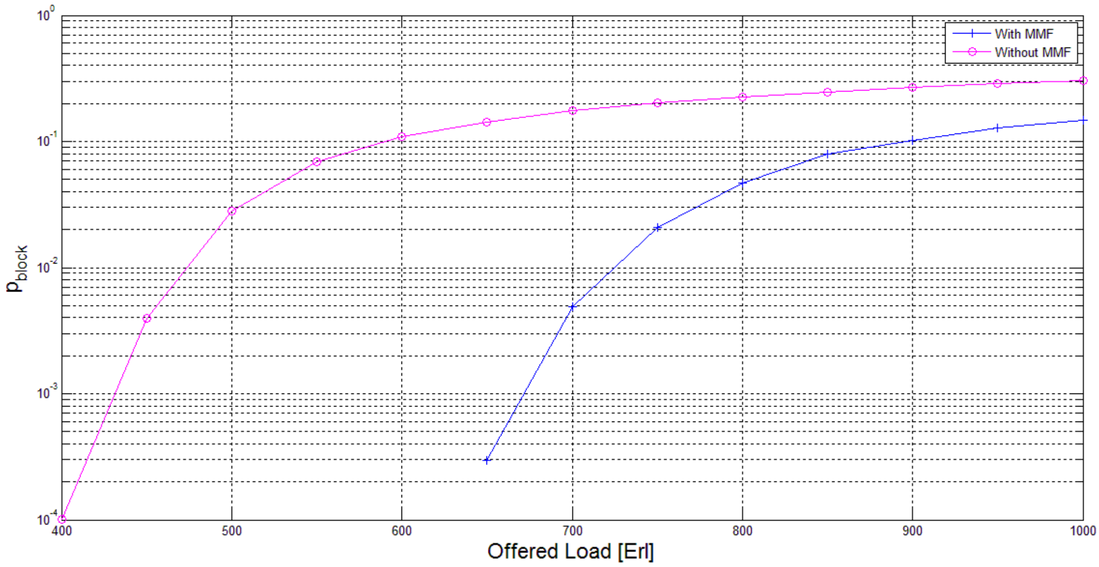

Figure 85. Blocking probability for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

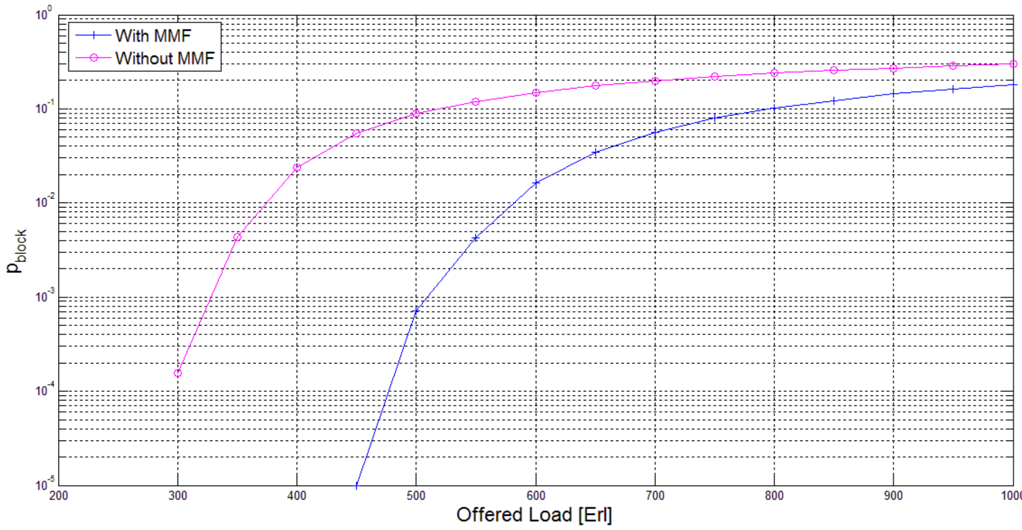

Figure 86. Blocking probability for the metro network in relation to the offered load (Not Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; transponder minimization; Holing Superchannel Grooming & Release, fixed DP-QPSK modulation format vs MMF)

The tendencies in the two graphs are to a great extent analogous with the ones characterized by uniformly distributed traffic.

In conclusion to this Subsection, we would like to point out that simulations have been carried out also for a network radius equal to 100 km, The obtained statistics have been neglected since not relevantly different from the scenario with 50km radius.

In fact, the change of the network radius from 50 to 100 km would imply a change in the circumference from ca. 314 to ca. 628 km. The 1-hop transmission distance changes from ca. 52 to ca. 104 km, the 2-hop transmission distance from ca. 104 to ca. 209 km, the 3-hop transmission distance from ca. 157 to 314 km. Higher transmission distances are rarely used, since they always lie on the longest path direction. Especially the very short transmission distances (1 hop and 2 hops) are mainly used in the MMF scheme. For such short transmission ranges, doubling the optical reach to cover does not lead to remarkable improvements. We report, as an example, the obtained graph of the blocking probability both for the network radius equal to 50 km and to 100 km. The scenario we consider has traffic uniformly distributed and the objective functions which aims to minimize the spectrum occupation. The obtained graph is reported in Figure 87. The graph supports our choice of not dwelling on different network radiuses since the performances are very similar. Larger network radiuses would go out of the focus, which is metropolitan networks.

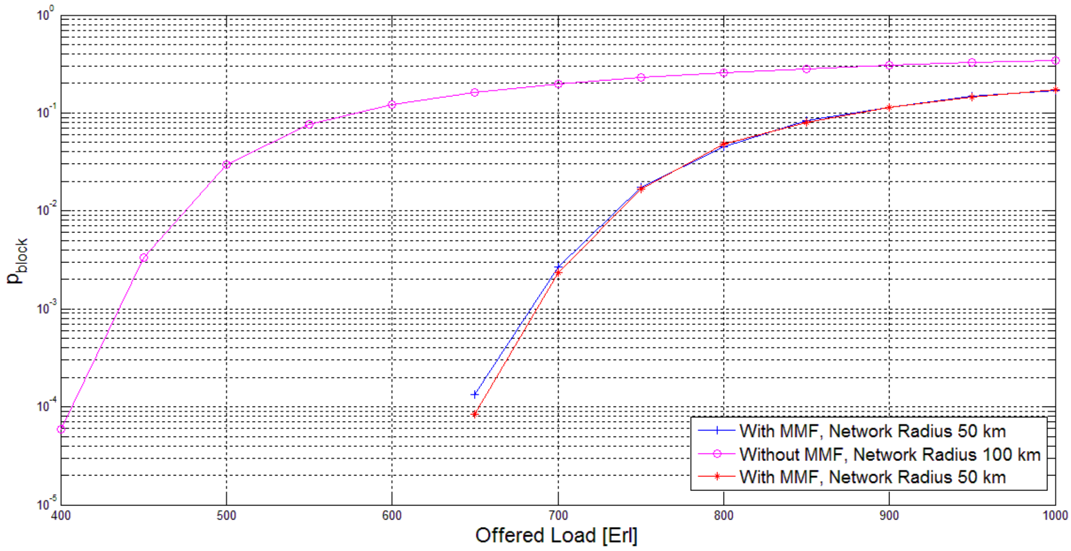

Figure 87. Blocking probability for the metro network in relation to the offered load (Uniform Traffic Distribution; flexible grid; Least Used Link Tie Resolution; Random Spectrum Assignment; spectrum minimization; Holing Superchannel Grooming & Release; fixed DP-QPSK modulation format vs MMF; network radius 50 or 100 km)

8 Conclusions and further works

8.1 Conclusions

The analysis carried out in this thesis show the potential advantages brought by the adoption of the flexible grid solution into a metro ring network.

We have shown improvements of up to three orders of magnitude with regard to the blocking probability of a flexible grid network, when compared to a DWDM network exploiting the same grooming capability. In the thesis, it is shown that the flexible solution makes a more efficient usage of the available bandwidth. A single transponder is accommodated over a less wide portion of optical spectrum. A set of lightpaths having the same source destination pair are merged together in a single frequency slot (the flexible entity which replaces DWDM channels); this allows to switch the set of lightpaths as a single entity, hence sparing inter-transponder guardbands within the frequency slot. The impact of guardbands on the total occupied spectrum is shown to be significantly smaller.

Introduction of the flexible grid leads to the definition of a new set ofpolicies for the RSA algorithm. Such policies are clockwise vs counterclockwise tie resolution, superchannel grooming, superchannel release, (flexible) spectrum assignment. The definition of these policies is shown not to affect remarkably the network performance, but instead they determine how fragmentally is allocated the optical spectrum. Fragmentation of the spectrum is the mirror of how i8ntensively the superchannel grooming, i.e. the main advantage brought by the flexible grid, is exploited.

Moreover, the additional benefits of the MMF feature are explored. We have shown that a flexible grid network exploiting the MMF capability presents a blocking probability which is up to three orders of magnitude lower, if compared with a fixed-modulation-format flexible network. In addition to this, significant saving also in terms of utilized transceivers are obtained.

8.2 Further works

The proposed RSA and RMLSA algorithms can be used for further studies in several aspects. Simulations of the proposed network model, but with a optical granularity compliant with the Rec. G.694.1 , i.e. equal to 12.5 GHz, can be carried out. More options for the set of policies can be proposed and experimented. The number of nodes belonging to the network can be varied. In particular, it can be analyzed if the introduction of an odd number of nodes leads significant effects thanks to the clockwise vs counterclockwise tie resolution policy. With regard to the objective function, it can be explored the possibility of dynamically set the two weight parameters α and β according to the network situation. This feature might be accompanied by the decay of the assumed infinite number or transponders.

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