Networking Benefits of Optimized Regenerator Placement and Hybrid Fiber Amplification

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Approval

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Abstract

The continuous growth of IP traffic is pushing telecom operators to carefully consider core network upgrades. Operators concern is to cope traffic increase, maximizing return over investments on already installed equipment. One of the simplest solutions to accommodate future core-network traffic is the extensive use of optical-electrical-optical (OEO) lightpath regenerators in nodes, relying on a mostly translucent network configuration. Besides reducing network flexibility, extensive OEOs usage is limited mainly by their power consumption, size and cost; hence, operators are looking for physical layer solutions alternative to them. The recent assessments of the capacity improvement granted by the upgrading of optical amplifiers, in this work we analyze if the selective upgrade of line amplifiers can be helpful in reducing the number of OEOs needed to sustain an existing traffic in two different network scenarios.

Hybrid amplifications schemes enable a distributed gain that decreases the equivalent noise figure (ENF) of the amplifiers and consequently the generated amplified spontaneous emission (ASE) noise, improving Quality-of-Transmission (QoT). Such improvement is colorless, since it affects the entire WDM channel comb. Thus, placing Hybrid Fiber Amplification (HFA) on network spans can bring global benefits to the allocated LPs and consequently to networking performance. Even if OEOs permit to completely reset propagation impairments by breaking LP transparency, they bring local benefits, since they operate on a per-channel basis. Understanding the trade-offs between these two techniques is therefore fundamental in the assessment of networking merit of physical layer technologies, to properly drive future core-network upgrades.

We focus on Pan-European and USNET topologies analyzing the impact of selectively introducing HFA with different pumping schemes and ENFs. We show that for USNET topology, HFA with 3 dB ENF, allows to completely remove the OEOs needed to sustain a uniform any-to-any traffic matrix with 200Gbps per connection, whereas for the Pan-European topology, adopting HFA with 0 dB ENF permits to save up to 75%of required OEOs.

Dedication

I am dedicating this thesis to my parents who always encouraged and motivated me to complete my thesis and achieve my goals.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Chapter 1

Introduction

The chapter Introduction gives the basic knowledge about the domain. It includes the background study, motivation, purpose, scope and objective of the thesis. Finally, thesis outline is discussed which represents the structure of the thesis document.

1.1 Fixed Grid Networks

There is continuous increase in number of users requesting for multimedia services and exponential growth of traffic, urges the need to provide high speed networks with huge bandwidths to fulfill the increasing needs of the clients. Fiber optic communications is one the solutions to fulfill the above mentioned demands. It uses different types of multiplexing techniques to cope with the increasing demand of bandwidth. Wavelength Division Multiplexing (WDM) is one of multiplexing techniques. Current backbone networks are WDM based networks supporting fixed grid allocation of wavelength channels. However fixed size frequency allocation in WDM has several drawbacks due to its coarse granularity and non-flexible nature. The main issue is mismatch between the required bandwidth and allocated one. WDM will become more spectrally inefficient with evolution of wavelength channel capacity beyond 100 Gb/s.
One of the simplest solutions to accommodate future core-network traffic is the extensive use of optical-electrical-optical (OEO) lightpath regenerators in nodes, relying on a mostly translucent rather than transparent network configuration. Besides reducing network flexibility, extensive OEOs usage is limited mainly by their power consumption, size and cost; hence, operators are looking for physical layer solutions alternative to them.
Following the recent assessments of the capacity improvement granted by the

upgrading of optical amplifiers [3-4], in this work we analyze if the selective upgrade of line amplifiers can be helpful in reducing the number of OEOs needed to sustain an existing traffic in two different network scenarios.

1.2 Problem Statement

In fixed grid networks problem of establishing connection is referred as the routing and wavelength assignment (RWA) problem, which is also known as NP-hard problem. In past times, WDM systems were designed to use one type of transponder, that is, they utilized a single-line rate (SLR). Recent advancements in transmission technologies & coherent reception have made possible the use of more than single type of transponder simultaneously, exploiting trade-offs between reach and cost available in the different devices to decrease the total network cost and improve the efficiency. Such networks are typically known as mixed-line rate (MLR), as opposed to the SLR case discussed above. The RWA problem for MLR WDM networks is more complicated than for SLR, as it involves the decisions for the type of transponder to use for each and every connection.

Both RWA, Routing and Spectrum Allocation (RSA) include a subproblem which addresses the problem of placement of regenerators in the network. WDM transceivers have specific transmission reach (the physical layer introduces various types of impairments: noise, interference, dispersion, etc.), and regenerators are used to establish long reach connections. However, in opposite to WDM networks, in flexible grid networks the transmission reach depends on the transmission configuration of the tunable Bandwidth Variable Transponders (BVT) and on the regenerators which can be controlled. Thus, regenerator placement in flex-grid networks also involves choosing the BVT configurations, making it more complicated than in fixed-grid networks[20].

The continuous growth of Internet traffic is pushing the need of telecommunication operators to carefully consider core network upgrades. Operators would like to sustain such traffic increase, while maximizing their return over investments on the installed equipment [1-2]. One of the simplest solutions to accommodate future core-network traffic is the extensive use of OEO lightpath regenerators in nodes, relying on a mostly translucent rather than transparent network configuration. Besides reducing network flexibility, extensive OEOs usage is limited mainly by their power consumption, size and cost; hence, operators are looking for physical layer solutions alternative to them. The problem is to find the solution that can facilitate operators to accommodate traffic increase with less or no OEO conversions.

1.2.1 Purpose

The main purpose of this research is to find if the selective upgrade of line amplifiers can be helpful in reducing the number of regenerators to sustain an existing traffic.

1.2.2 Scope

The scope of our research is to provide benefit globally to the allocated light-paths and consequently to the overall networking performance by reducing number of regenerators.

1.2.3 Objectives

The objectives of thesis is to place and minimize the number of regenerators.

1.2.4 Thesis Outline

Rest of the thesis document is organized as follows

- Chapter 1: It gives the introduction of research domain, describes the problem statement, purpose, scope and objectives of thesis.
- Chapter 2: It describes introduction of WDM.
- Chapter 3: It includes previous work done in the field of regenerator optimization, regenerator placement and assignment.
- Chapter 4: It explains our proposed schemes and simulation setup for the validity of proposed scheme.
- Chapter 5: It presents the results of proposed technique
- Chapter 6: It provides the conclusion and comments on the entire work

Chapter 2

Optical Network Fundamentals

2.1 Introduction

The recent developments of social networking, bandwidth hungry applications and data centre networks has increased the demand of internet traffic by many folds. With the prediction of explosive internet traffic growth in future years [16], there is need of networks that can cope up with increasing need of internet traffic along with capability to handle future internet traffic demands. Optical networks using optical fiber for transmitting data are considered promising solution to handle internet traffic demands as it offers huge amount of bandwidth. With Wavelength Division Multiplexing technology, each fiber can support wavelength up to 100 Gb/s or higher [17,18] . User demands are satisfied by assigning the wavelength and routing to form lightpaths with the help of RWA algorithms, results in wavelength routed networks. Besides popularity of WDM, its coarse and rigid nature of wavelength assignment makes it inefficient. WDM network divides the fiber into equal fixed size bandwidth channels. When traffic demand requires multiple wavelengths (super wavelength traffic) guard bands between these multiple wavelengths leads to the under-utilization of available spectrum resources as shown in Fig. 2.1. [15,19]

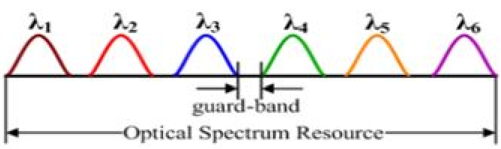

Figure 2.1: Wavelength Assignment in WDM

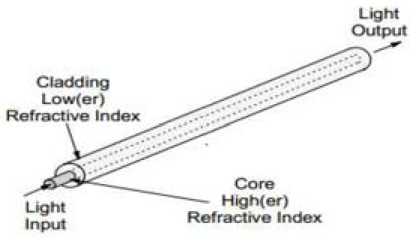

Figure 2.2: Basic Principle of Light Transmission on Optical Fiber

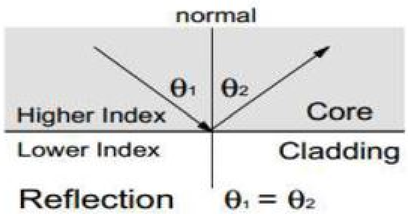

Figure 2.3: Reflection of Optical Signal

2.2 Basics of Optical Communication

Optical networks is a way of communication from source to destination in form of optical signal. Optical signal is electromagnetic wave that is modulated to carry information over the short or long distances [23]. To transmit the modulated signal, special kind of cables are used. These cables are called optical fibers and are made up of numerous long and thin strands of pure glass having diameter size equal to the human hair. When optical signal comes in the fiber, it confines in the fiber till the other end. This is why signal faces minimal loss while passing through the fiber.

Upon closely looking Fig. 2.2, there are three elements of fiber

- Core: Through which the light passes
- Cladding: Optical material outside core which enables reflection of light back to core.
- Buffer Coating: Plastic material that covers the fiber, protects it from outside environment like moist and damage.

Optical signal propagates through the fiber on the laws of refraction and reflection. Refraction occurs when signal faces change in speed moves from medium of different densities. As fiber is not always laid perfectly straight, light passing through fiber repeatedly bounces off towards cladding and with

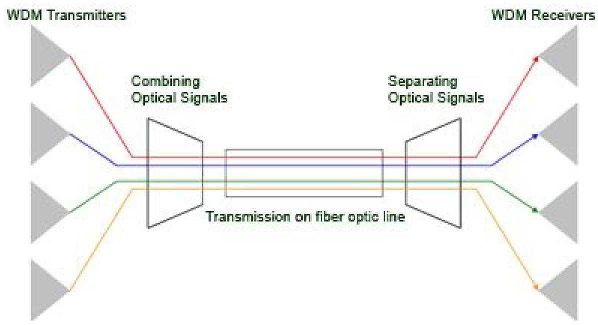

Figure 2.4: Wavelength Multiplexing and Demultiplexing

the phenomena of reflection, it comes back to core. This is how signal propagates through the fiber. When light propagates from medium of higher refractive index to medium of lower refractive index at incident angle greater than critical angle then signal keeps moving into the medium. This is called total internal reflection. Critical angle is determined by the refractive index of core and cladding with the help of Snells Law. Hence to keep signal moving in the medium, it must be guided above critical angle until it reaches its destination.[16]

2.3 Wavelength Division Multiplexing

Wavelength Division Multiplexing is optical communication technology which carries various optical signals of different modulation schemes over the single fibre. WDM allows two way communication through single fibre with enhanced capacity. Optical network has huge bandwidth capacity which is equally divided into small bandwidth channels. In optical domain, at transmitter side there are number of multiplexers that multiplex multiple signals onto single fibre and at the receiver side there are number of demultiplexers to demultiplex the multiplexed signal. Transmitter consists of laser, modulator to modulate the signal and light source creates optical signal either at fixed or tunable wavelength. Receiver consists photodiode detector to convert optical signal back to electrical signal[21]. Multiplexing increases network capacity without lying more fibres. This multiplexing system has security as compared to other communication systems from tapping and safe from crosstalk[22].

Optical networks have many times higher spectrum and bandwidth than RF spectrum but degrades due to attenuation in wavelength. Other limitation factors like degradation of refractive index and fibre imperfection. These limitations forces us to use window 1300nm (0.32dB/km)-1550nm

Parameters	WDM	CWDM	DWDM
Channel Spacing	1310nm & 1550nm	Large,1.6nm-25nm	Small,1.6nm or less
No of base bands used	C(1521-1560 nm)	S(1480-1520 nm)C(1521-1560 nm),L(1561-1620 nm)	C(1521-1560 nm),L(1561-1620 nm)
Cost per Channel	Low	Low	High
No of Channels Delivered	2	17-18 most	hundreds of channel possible
Best application	PON	Short haul, Metro	Long Haul

Figure 2.5: Types of WDM Networks

(0.2dB/km), with less attenuation.

There are three types on basis of wavelength patterns.

- CWDM (Coarse Wavelength Division Multiplexing)
- DWDM (Dense Wavelength Division Multiplexing)
- WDM (Wavelength Channel Multiplexing)

2.3.1 Coarse Wavelength Division Multiplexing

CWDM is the first step to deploy optical communication system because of its low cost. It provides 16 wavelengths and can be deployed at networks of 80 km and amplifiers are not required because of the larger spaces between channels. It supports the transfer rate of 2.5 Gbps and goes up to 10Gbps.

2.3.2 Dense Wavelength Division Multiplexing

DWDM is another type which supports larger distances with higher data rates. It supports 44-88 wavelengths or channels per fiber. DWDM data rates can go up to 100 Gbps per wavelength and each wavelength can perform multiple services. Channel spacing is defined by the ITU and can support the range from 50 GHz to 100 GHz, even 200 GHz these days. It can support even 96 wavelengths with mixed services and cover distance up to 3000 km with the help of amplifiers while compensator enhances the fiber capacity with factor of 100. This technology is costly as compared to CWDM and extremely useful these days providing higher capacity and covering longer distances [22].

2.4 Benefits of WDM Network

WDM is the technology currently deployed in core networks. It provides better features than any other types of communication with customer satisfaction. Following features makes this communication technology significant

2.4.1 Capacity Upgrade

Optical communication provides higher bandwidth than other communication technologies. It uses light to carry data and one light beam can carry different wavelengths which are multiplexed onto single fiber. The capability of single fiber carrying multiple wavelengths on a single fiber increases network capacity.

2.4.2 Transparency

This feature allows data communication at different bit rates. There are number of communication protocols and puts less constraint on how to send data. It is used for multiple high rate data communication applications.

2.4.3 Wavelength Re-usability

This feature of WDM allows to use one wavelength again and again for connections in different links. Wavelength re-useability features increases the network capacity.

2.4.4 Reliability

These networks are reliable because crosstalk is very less and there is facility to reroute the traffic in case of link failure. It will prevent loss due to link failure.

2.4.5 Scalability

WDM networks provides provision of adding additional equipment at the transmitter and receiver side to accommodate more people. This is just possible because of the flexible nature of these networks[24].

2.5 Network Design

Designing a network involves two steps i.e logical topology design, routing and wavelength assignment. In logical topology design, lightpaths are establishment and routing of lightpaths is done in RWA.

2.5.1 Logical Topology Design

Logical Topology Design is the phase of network design where lightpaths are established either direct or indirect with provided information. Provided information could be either of two, both physical topology and traffic matrix or just traffic matrix. Below are some important points we have to keep in mind while establishing lightpaths.

Transponder Capacity If transponder given capacity is suppose 100 Gb/s and we have traffic from source to destination above the range of transponder capacity i.e. 150 Gb/s or 200 Gb/s etc. To cope this we have to perform one of the following

1. We either have to increase transponder capacity

2. Establish extra lightpath to accommodate traffic

Transmission Reach Suppose we have maximum reach of 4000 with modulation scheme of BPSK. We have to send data from source to destination via hops and total reach is 4500 so there is need to establish one light path from source to hop and again hop to destination. This request of sending data from source to destination requires two light paths.

2.5.2 Routing and Wavelength Assignment

There must be established connection between source and destination in order to send data. The connection established between source and sink is called light path or optical path. Finding route for the established optical path and assigning wavelength to it is called RWA [25]. RWA is divided into following two parts.

1. Routing
2. Wavelength Assignment

In RWA problem, there are two types of lightpath establishment.

- Static Lightpath Establishment - This reduces number of wavelengths needed per connection.
- Dynamic Lightpath Establishment - This reduces blocking probability.

2.6 Existing Wavelength Assignment Algorithms

There are different types of wavelength assignment algorithms. It is important step on which quality of whole network depends after establishing light paths and finding routes.

2.6.1 Random Fit

In this algorithm all the possible paths from source to sink and all the wavelengths which are yet not assigned to any data transmission are determined. It assigns wavelength randomly to transmit data from source to destination[26].

2.6.2 First Fit Wavelength Assignment

In this algorithm, first available wavelength is assigned to the data transmission from source to sink.

2.6.3 Most Wavelength Used Algorithm

Most wavelength used is the wavelength which is the used by most links. This algorithm selects the most used wavelength from the available wavelengths.

2.7 Constraints

There are two constraints which needs to be fulfilled when assigning wavelengths.

Wavelength Continuity Constraint - Same wavelength must be used all over the path from source to destination.

Distinct Wavelength Constraint - All the light paths on the same link must be assigned different wavelengths [27].

Chapter 3

Literature

This chapter gives insight to the work of regenerator minimization and hybrid amplification done in recent years. In [28] improvement in transmission performance is achieved due to hybrid amplification of EDFA and Raman Amplifiers. They have used three types of fibers Standard Single Mode Fiber (SSMF), Large Area Pure Silica Core Fiber (LAPSCF) and Large Effective Area Fiber (LEAF). Because of hybrid amplification, distance extended to 2054, 2952 and 1341 km for SSMF, LAPSCF and LEAF from 1110, 1921 and 789 km respectively at 3.37*10-2 pre-FEC threshold.

In [29] they have proposed heuristic based algorithm COR2P Cross Optimization RWA and Regeneration Placement aims to minimize regeneration sites while minimizing number of regenerators required in network. Regenerators are placed whenever Bit Error Rate (BER) calculated value decreases than threshold value and BER value is calculated by BER predictor tool. BER calculation considers four impairments named Chromatic Dispersion, Non Linear phase shift, Amplified Spontaneous Emission and Polarization Mode Dispersion. Having network topology and lightpaths, this algorithm finds RWA and places regenerators in order to satisfy Quality-of-Transmission (QoT) constraints. Their algorithm has three steps and first is preliminary routing involves two steps.

First sorting of lightpaths with decreasing BER and accommodating the request which is most effected by transmission impairments first. Second is to accommodate request one by one and if there is no wavelength free path then step 3 is processed which is explained below. That means lightpaths can be satisfied due to placed regenerators which relaxes the wavelength continuity constraint.

Second step is potential regenerator placement. This step has set of lightpaths obtained in result of step 1. To find the potential regenerator place, the have considered counter at each node and when the signal degrades counter value increments of preceding node and restarts the quality check from that node. After quality check of all lightpaths, they are sorted in decreasing order of number of counters. The first R nodes are those nodes where regeneration is required. R represents the initial number of regeneration sites in the network. P is the ratio of initial regeneration sites by the total number of nodes. They expect to effectively deploy the regeneration sites can be reduced by selecting the p judiciously.

Third step is effective RWA and regenerator placement where they considers lightpaths routed in step 1 and assigns wavelength according to Best BER Fit (BBF) assignment strategy. Path is assigned wavelength according to the quality of transmission requirements by BBF strategy and saves the wavelengths better suited in context of BER for longer lightpaths. In case of wavelength unavailability which can satisfy the QoT requirements, lightpaths requires regenerators. Regenerators are deployed according to the cost function which not only aims to optimize the deployed regenerators but also concentrate the regenerators in nodes. Cost Function of path tries regeneration on different places and computes the cost of those combinations. At the end it selects the combination of path with lowest cost.

3R regenerators and transponders are expensive devices in optical networks share a large part in overall cost of the network operation and deployment. It is obvious to determine the number of regenerators to route a lightpath and number of regenerators needed depends upon many factors like optical performance of routing and line interface, 3R regenerator placement algorithms and wavelength assignment[30,31].

Optical networks use wavelength routing to establish connection between source and destination. Erbium Doped (EDFA) causes noise that degrades the signal which depends upon the distance between the source and destination. Interest has been developed due to traffic load and software defined transceivers in designing networks that adapt transmission parameters according to physical layer. One approach is to study the adaptation of modulation formats and Forward Error Correction (FEC) according to physical layer parameter which is Signal to Noise ratio (SNR) of different routes. This problem has been reported in different papers. Other aspect of optical networks is EDFA which is characterized by Noise Figure (NF) and the value of NF is used 3 dB minimum theoretically but reported 5-7 dB commercially available amplifiers.

In [3] they have analyzed the effect of amplifier NF on the throughput and surprisingly found no major inpmact on throughput. They have analyzed different network topologies with transceivers consuming channel capacity or discrete constellations with ideal Soft and Hard decision FEC (SD-FEC , HD-FEC). They have considered three different network topologies repre-

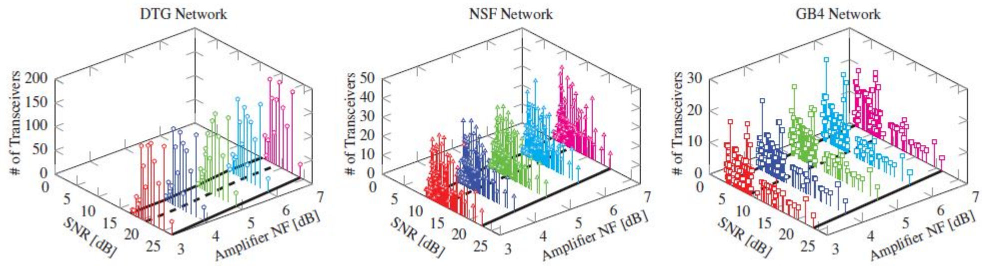

Figure 3.1: Number of Transceivers for different networks and different Amplifier NFs

sentative of three different scales country, continental and transcontinental. To calculate the SNR they have used SNR = P/(N_s(P_{ASE}+P3)), Where P is the launch power at each channel P_{ASE} is the ASE noise added after each span is the non-linear coefficient calculated by incoherent GN model Fiber attenuation, non-linear coefficient and dispersion is considered as .22 dB/km, 1.3 1/W/km and 16.7ps/nm/km respectively with 32Gb and 80 km per span. Different values of NF 3,4,5,6,7 leads to different values of P_{ASE} 0.47,0.59,0.75,0.94,1.18 W. Launch power P* is computed by

$$\sqrt[3]{PASE/(2*)}$$

which gives 1.66,1.33,0.99,0.66,0.33 dBm. They have gained the maximum throughput under uniform traffic demand and assuming transceivers can achieve the channel capacity which is computed by C = $2\log_2$(1+SNR).

Fig. 3.1 showing the trend of lowering SNR when NF increases between the SNR and amplifiers for different values of NF for all considered topologies. One dB increase in NF results in one dB decrease in noise power, ultimately increases 1/3 dB in power launch. As expected, Increase in NF causes decrease in network throughput. Results show the relative loss caused due to increase in value of NF as network increases. For one topology results reported 4% decrease in throughput caused due to 1 dB increase in NF while for other topologies 5.5% and 7% decrease reported. Highest impact is observed in large networks of the noise figure for network throughput. In [14] authors have addressed the comparison of Lightpath Regeneration and Digital Back Propagation as Quality of Transmission enhancing techniques and showed that ISC-DBP reduces substantial amount of regenerators in considered networks for PM-QPSK (100 Gbps) transceivers.

Other papers evaluate DBP on point to point fiber systems while [14] analyze DBP on optical network. The have evaluated the advantages of ISC-DBP on three different networks, US, PAN_EU and German topology

Figure 3.2: Percentage of ULP enabled by DBP and LR in case of PM_QPSK

considering two types of transceivers PM-QPSK (100 Gbps) and PM-16QAM (200 Gbps). All the links have same power for the lightpaths (LPs) and optimized according to Locally Optimized Globally Optimized (LOGO) principle. Lightpaths have been assigned channels according to first fit assignment algorithm and to establish transparent connection, lightpaths OSNR value should be greater than threshold generated by the modulation format and the Forward Error Correction (FEC) code. The parameter for QoT of lightpaths is Generalized Optical Signal to Noise ratio (OSNR) considering Nonlinear impairments and ASE noise. They have used three ways to enhance QoT parameter via Lightpath regeneration, ISC-DBP at receiver and mixture of one and two enhancement technique. Lightpath is considered Out of Service (OOS) if none of these enhancing techniques is effective. ISC-DBP is effective than Lightpath Regeneration as it doesnot effect the transparency of network. Side channels can be dropped and added at any node because of multichannel DBP which makes multichannel DBP ineffective. Advantage of ISC-DBP is computed as how many regenerators can be saved as compared to Lightpath regeneration. In case of ISC-DBP OSNR is calculated by the following formula

$$\mathrm{OSNR}_{DBP}= \mathrm{P}_{TX}/\ (\mathrm{P}_{ASE}+\mathrm{P}_{NLI}-\mathrm{P}_{SCI})$$

P_{TX} is defined power as per LOGO P_{NLI} and P_{ASE} are powers of NLI and ASE noise. The NLI generated by the single channel up to itself is called self channel interference (SCI) which is removed by Ideal Single Channel DBP. PSCI is computed by Enhanced Gaussian Noise Model and NLI and ASE is computed by Incoherent Gaussian Noise Model. ISC-DBP can provide more power per lightpath than the LOGO and analysis in considered topologies reported change in OSNR less than 0.08 dB so authors of the paper used LOGO approach.

In Fig. 3.2 it is shown that 67% of the Underperforming lightpaths (ULPs) are enabled by the ISC-DBP and 33% are enabled by lighpath regeneration

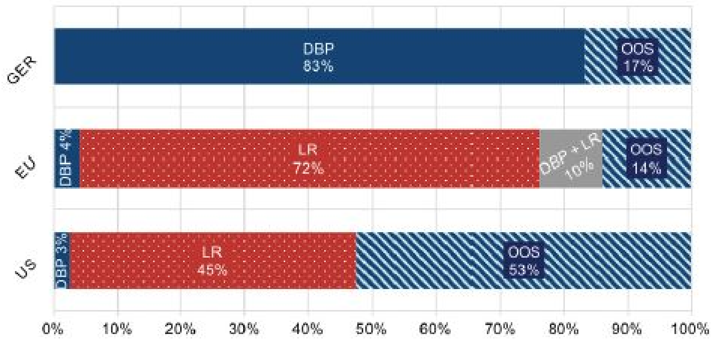

Figure 3.3: Percentage of ULP enabled by DBP,LR, DBP+LR and out of service (OOS) in case of PM_16QAM

for the case of EU topology whereas in case of US_NET 50% ULPs enabled by DBP and 50% enabled by LR. In case of German topology there is no ULP for PM_QPSK. Decrease in 50% from 67% from EU topology to US topology is due to the longer average link length of US topology. Due to this many lightpaths may undergo QoT transmission that cannot be recovered by DBP.

In Fig. 3.3 PM_16QAM modulation format is used with a threshold value of 15.13 dB. Fig. 3.3 shows that in German topology DBP enables 83% of the ULP and decreases to 4% and 3% in EU topology and US topology respectively. LR is the effective solution for these topologies for enabling ULPs and this is because of considered countermeasures towards poor quality of transmission of lightpaths. LR work on individual nodes and DBP works on whole lightpath from source to destination effective when there is little gap of LP with respect to required OSNR. In EU long distance, multihops combination of DBP and LR is used to enable 10% of ULPs. This paper introduces the need for improving amplifiers and/or fibers to improve the OSNR and suggests the need of Hybrid Fiber Amplification to reduce the noise figure with Raman and Erbium Doped Fiber Amplification (EDFA) amplification. Optical Transport Networks (OTN) are divided into three networks

- Transparent Networks: These networks send data from source to destination without regenerators.
- Opaque Networks: These networks include regenerators at every node
- Translucent Networks: These networks deploy regenerators at the selected nodes.

Other Quality of Transmission estimators in literature are OSNR, Bit Error Rate or Q-Factor[32].

Chapter 4

Methodology Results

We focus on a 28-nodes 41-links Pan-European [6] and a 24-nodes 43-links USNET [7] topologies analyzing the impact of selectively introducing Hybrid Fiber Amplification (HFA) with different pumping schemes and ENFs. We show that for the USNET topology, selectively placing HFA with 3 dB ENF, allows to completely remove the OEOs needed to sustain a uniform any-to-any traffic matrix with 200Gbps per connection, whereas for the Pan-European topology, adopting HFA with 0 dB ENF permits to save up to 75% of required OEOs.
We consider 80 channels, fixed-grid reconfigurable WDM optical networks with links operated at their optimal power as prescribed by the Locally-Optimized-Globally-Optimized (LOGO) setup [8-9]. We assume network nodes equipped with rigid transceiver, i.e. operating with a fixed modulation format. Hence, to establish node-to-node transparent connections, the QoT of each LP must be larger than a given threshold, established by the modulation format and by Forward Error Correction (FEC) coding. The metric defining the QoT of lightpaths is the generalized OSNR, computed through the incoherent Gaussian Noise (IGN) model, assuming full spectral load [10-11]. If the OSNR of a LP is below threshold, the LP is considered to be ULP, and thus requires an OEO in an intermediate node to reset propagation impairments by breaking lightpath transparency. We consider the allocation of an any-to-any matrix using a k-max best QoT based routing with first fit wavelength assignment [11]. In this paper we use k-max=8 which avoids any wavelength blocking. For lightpaths below threshold, OEOs are placed using a greedy strategy, based on the minimum stops algorithm [12]. To compute the QoT benefit enabled by HFA, we consider the amplification strategy suggested in [5] and adopted in [4]. Namely, we assume to adopt HFA with counter propagating pumping scheme in the moderate pumping regime (MPR), in which Raman amplification recovers up to 60% of the

Table 4.1: Simulation Parameters

Parameters	**Values**
Wavelengths	80 per fiber
Fiber Type	Single Mode Fiber
Dispersion	16.7 ps/nm/km
Attenuation	0.2 dB/km
Modulation Schemes	QPSK , 16QAM
Data Rates	100 or 200 Gb/s
OSNR Threshold	8.5 or 15.1 dB
ENF in case of EDFA	5 dB
ENF in case of HFA	0 dB in case of HFA Amplification
Gross Symbol Rate	32GBaud
Topologies	USNET and PAN_EU

span loss in dB units. In such a regime, pump depletion and Raman-induced Non-Linear impairments (NLI) enhancement are negligible and the ENF is independent of the power per channel [5]. Therefore, HFA operated in the MPR is suitable for reconfigurable optical networks as the LOGO control plan can be still applied taking advantage of the ENF reduction and without caring about channelsadd/drop. Depending on the pumping levels, the ENF can be reduced from 5 dB down to 0 dB [5], allowing a consequent optimal power reduction and OSNR enhancement. To establish the networking benefit of selective HFA update, we consider the full list of LPs enabled by OEOs, and for each of them, we upgrade one-by-one the spans of links that they traverse, starting from the source node and without considering OEOs. For each span update we verify if the LP can be transparently routed to its destination. If so, the process is stopped, the selective HFA update are consolidated, and the OSNRs of all the LPs traversing the updated spans are recomputed. If upgrading to HFA all the spans traversed by the LP is not sufficient for transparent transmission, we try to consider if mixed OEO+HFA solutions permit to save OEOs with respect to the starting full-OEO solution. If not, the LP can be operated only by using OEOs.

4.1 Performance Parameters

Here is list of the parameters are shown in table 4.1:

Figure 4.1: PAN Topology

4.2 Performance Results

We perform the described analysis in two different network scenarios. We consider a 28-nodes 41-links Pan-European [6] Fig. 4.1 and a 24-nodes 43-links USNET [7] Fig. 4.2. Links are assumed to be bidirectional,uniform and uncompensated fiber-pairs consisting of Single Mode Fiber (SMF) with 0.2 dB/km attenuation, 16.7 ps/nm/km dispersion and 1.3 1/W/km non-linear coefficient, and operating on the 50 GHz grid, exploiting up to 80 DWDM channels per link. To compute the initial RWA solution and the related OEO placement, we consider using lumped EDFA amplification with 5 dB noise figure and assume 18 dB excess node loss recovered by an additional amplifier. We consider the use of rigid transceivers with PM-16QAM. We suppose a gross symbol rate $R_{s,G}$ of 32 GBaud including a 28% FECprotocol overhead, and a corresponding pre- FEC BER level of 4.10^{-3}. Thus, lightpaths can carry a net rate of 200 Gbps for traffic payload. The minimum required OSNR calculated in $B_{ch}=R_{s,G}$ is 15.1 dB.

Fig. 4.2 shows the distribution of enabling technologies for ULPs for the Pan-European topology vs. the equivalent noise figure of HFAs. For this topology, 572 lightpaths out of 756 are underperforming, requiring a total of 1108 OEOs to be operative, and corresponding to an average of 1.93 OEOs per LP. The case with ENF set to 5 dB corresponds to the full-OEO scenario, i.e., the setup for which the number of LPs requiring OEOs is maximum and to which we refer for the evaluation of HFA benefits expressed as a percentage. It can be noted that selectively decreasing the ENF to 4.5 dB permits to shrink the percentage of lightapths enabled by OEO to 75% of the total ULPs. Among the remaining 25% of ULPs, 5% are enabled by HFA only. The last 20% are now enabled by mixed OEO+HFA solutions, since in the full-OEO scenario they were requiring more than one OEO. By further decreasing the ENF to 0 dB, the number of OEO-enabled lightpaths goes down

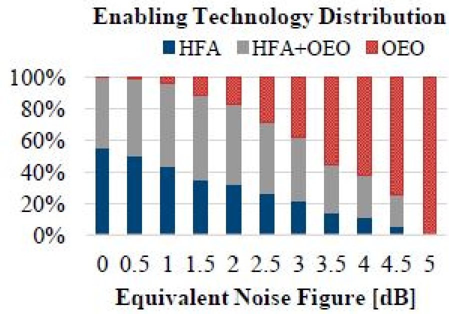

Figure 4.2: Distribution of enabling technologies for ULPs vs ENF.

to 0.35% of the total. On the other hand, the percentage of HFA-enabled lightpaths steadily increases at an average rate of 11% per dB of ENF reduction, reaching a maximum of 55% for the maximum pumping power scheme, i.e., the one delivering the best ENF of 0 dB. A similar trend can be observed for lightpaths enabled by mixed HFA+OEO solutions, for which the average rate of increase in distribution is 9% per dB of ENF decrease. Consequently, mixed application of OEO and HFA enables 45% of LPs at ENF=0 dB. Thanks to the selective use of HFAs, the number of lightpaths enabled by full-OEO solutions decreases at the rate of 20% per dB of ENF reduction.Keeping the attention to Fig. 4.2, it can be noted that the increase rate for number of lightpaths enabled by mixed OEO+HFA solutions is growing quite rapidly, displaying an increase of 17% per dB of ENF reduction up to ENF=2 dB. If ENF is further reduced, the trend is inverted, as the number of LPs enabled by mixed OEO+HFA solutions decreases in favor of lightpaths enabled by full-HFA solutions.

Fig. 4.3 shows the percentage of OEOs that can be removed vs. the ENF of HFAs. Note that this figure delivers additional information with respect to Fig. 4.2, as it takes into account the number of OEOs saved by using either HFA only or mixed OEO+HFA strategies. The trend is quite linear and, on average, 15% of OEOs can be saved per dB of ENF reduction. 50% of required OEOs can be removed when selectively upgrading network spans to HFA with a pumping scheme enabling a 2 dB ENF, while enlarging the pumping power in order to obtain ENF of 0 dB, up to 75% of the original number of OEOs can be removed.

In the PAN-EU network topology the average link length is quite long, being 637 km. Hence, due to the consequent presence of LPs experiencing large loss, 25% of OEOs are in any case required to sustain the targeted 200G any-to-any traffic. To fully remove OEOs, other techniques to enhance lightpaths QoT must be considered, e.g., advanced Digital Processing (DSP)

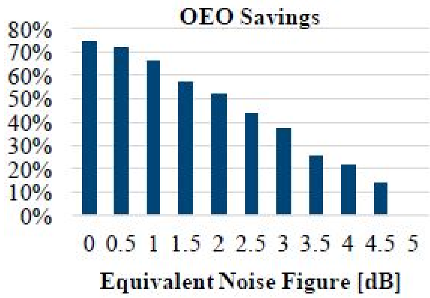

Figure 4.3: Percentage of saved OEO vs ENF.

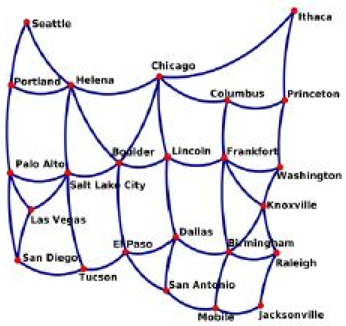

Figure 4.4: USNET Topology

techniques at transmitter and receiver such as Probabilistic Shaping (PS) [13] or Digital Back Propagation (DBP) [14]. Fig. 4.4 refers to the second network topology, i.e., to the US scenario. In this case, the average link length is 308 km, shorter than in the Pan-EU topology. Therefore, on average, links are less lossy than in the PAN-EU topology, and it is reasonable to expect a larger average OSNR per link, thus a smaller number of ULPs. Indeed, performing the exact calculation, only 29 lightpaths out of 552 are underperforming. Moreover, there are no lightpaths enabled by more than one OEO yet in the full-OEO scenario, i.e., for ENF = 5 dB.

For this topology, selectively introducing HFA with ENF=4.5 dB only 0.5 dB reduction is already effective and permits to reduce the number of required OEOs by 41%. Considering a mild pumping increase enabling HFAs with ENF=3 dB to upgrade the network, all ULPs can be transparently routed and all OEOs can be removed, as it can be observed in Fig. 4.5 Fig. 4.6.

For the US scenario, adopting pumping schemes based on larger power to further reduce the ENF is obviously useless in OEO reduction, but it can

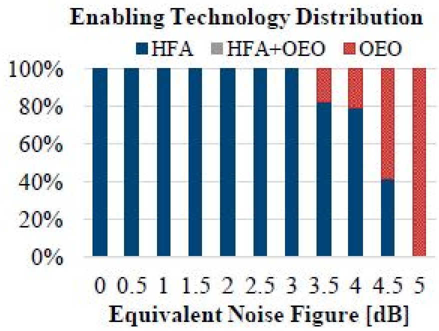

Figure 4.5: Distribution of enabling technologies for ULPs vs ENF.

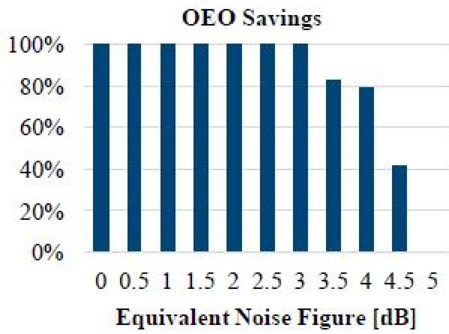

Figure 4.6: Percentage of saved OEO vs ENF.

be useful to decrease the overall number of amplifiers needing HFA update to get an OEO-free transparent optical network for the allocated traffic.

Summarizing this effect, for the US topology, introducing HFAs with ENF=0 dB permits to remove 100% of required OEOs by upgrading only 44 spans out of 346, corresponding to 13% of the total. To achieve the result of OEO free network using HFAs with ENF=3 dB, 69 spans 20% of the total number must be upgraded introducing some Raman pumping. This behavior, properly complemented with techno-economic analysis, can be fruitfully exploited to plan physical layer upgrades, trading-off costs and benefits.

Chapter 5

Conclusions

5.1 Conclusions

We addressed the evaluation of the network benefit brought by selective upgrade of optical line amplifiers based on Erbium technology to better performing Hybrid Raman/Erbium Fiber Amplifiers. We analyzed how the selectively introducing HFAs can greatly reduce the number of required OEOs in reconfigurable optical networks. For PAN-EU topology, 572 lightpaths out of 756 are underperforming, requiring a total of 1108 OEOs to be operative, and corresponding to an average of 1.93 OEOs per LP. The case with ENF set to 5 dB corresponds to the full-OEO scenario, i.e., the setup for which the number of LPs requiring OEOs is maximum and to which we refer for the evaluation of HFA benefits expressed as a percentage. It can be noted that selectively decreasing the ENF to 4.5 dB permits to shrink the percentage of lightapths enabled by OEO to 75% of the total ULPs. Likewise 75% reduction of OEOs can be achieved by selectively introducing HFAs with 0 dB ENF.

In USNET only 29 lightpaths out of 552 are underperforming. Moreover, there are no lightpaths enabled by more than one OEO yet in the full-OEO scenario, i.e., for ENF = 5 dB.In this topology selectively introducing HFA with ENF=4.5 dB only 0.5 dB reduction is already effective and permits to reduce the number of required OEOs by 41%. Considering a mild pumping increase enabling HFAs with ENF=3 dB to upgrade the network, all ULPs can be transparently routed and all OEOs can be removed. Smaller savings can be traded-off with less performing pumping schemes yielding larger ENFs. The effectiveness of this upgrade strategy decreases with the network size. Thus, other QoT enhancing techniques must complement it to achieve full network transparency via complete OEOs removal.

Chapter 6

Future Work

As a future work, we can study the impact of hybrid amplification with advanced digital processing techniques to evaluate how the joint selective introduction of improved hybrid amplification technologies at inline amplification sites and advanced digital signal processing techniques at transceivers allows to greatly reduce the number of required OEO regenerators in transparent optical networks. Quantitative studies focusing on two different DSP techniques: digital back-propagation and probabilistic shaping can show how much benefit we can achieve using these techniques.

Chapter 7

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