A Planned Amplification approach at WDM systems simulators

João Acciaioli Valverde
Instituto Superior Técnico
Universidade de Lisboa
joao.acciaioli@tecnico.ulisboa.pt

Abstract—Nowadays metropolitan and long haul optical networks have evolved into complex Wavelength Division Multiplexing (WDM) systems. The present dissertation presents and studies the viability of an unusual scalable optical simulation paradigm, i.e. a simulator which guarantees the system functionality when adding new WDM channels.

Traditionally, optical simulators calculate the parameters of optical amplifiers considering its entering signals, of which optical amplification depends. Consequently, adding or dropping WDM channels has impact on the achieved amplifiers gain and noise figure, thus making the performance of unchanged channels to fluctuate.

In this work an optical simulation method that defies such reality was implemented and studied. This method, baptized Planned Amplification simulation method, trades accuracy for channel performance stability. Through the proposed paradigm, an existing channel performance shall not fluctuate when adding or dropping other WDM channels.

In order to analyze and conclude on the viability of the Planned Amplification simulator, several simulations of different links were performed. Results of this simulator and of a traditional one (Real Amplification) were compared so that the introduced error of granting stable channels performance could be quantified. The highest measured channel performance error for point-to-point maximum reachability links was 0.911 dB, For a mesh network emulating a real network scenario, the highest registered error was −0.096 dB.

I. INTRODUCTION

The Internet Protocol (IP) traffic has globally increased fivefold between 2009 and 2014 and that it is expected to increase threefold over the next five years. The Annual global IP traffic might pass the zettabyte threshold by 2016 and might even reach 2 zettabytes per year by 2019. Metropolitan traffic has surpassed long haul traffic since 2014 and it is expected to account for 66 % of the total IP traffic by 2019. Moreover, busy-hour traffic is growing faster than average traffic, by factors of 3.9 and 3.2 between 2014 and 2019, respectively [5].

Since service providers plan network capacity according to peak growth, rather than average growth, the importance of such information becomes clear. Peak traffic dictates the demand requested from the service providers, consequently dictating demand requested from the networks infrastructure. Fixed broadband bandwidths improvements are likely to continue and predictions state that by 2018 these bandwidths will nearly triple the 2013 ones, from 16.1 Mbps to 42.2 Mbps, due to fiber to the home solutions, among others factors [5].

Behind these numbers lies a fiber optic communication infrastructure which is of absolute necessity to Internet as it is known today. The optical fiber has been replacing the twisted pair copper cables due to the significantly higher bandwidth and higher distance reachability. Since in the optical domain light frequency (hundreds of THz) carries the signal, it will not be significantly affected by Electromagnetic interference, which is the main responsible for the twisted copper pair limitations. This trend is most evident in backbone metropolitan and long haul networks, since they are the ones facing the most challenging demands. It becomes easy to underestimate the importance of this transmission technology since from a network user perspective, one is absolutely unaware of the transmission medium. The fact is that every network service between American and European soil, for example, is nowadays enabled by optical links. Transoceanic transmission systems undoubtedly illustrate the how much fiber optics have revolutionized telecommunications [1].

It is nowadays very common to witness the deployment of systems in which the system’s the installed capacity is not fully used. Network administrators are aware of how fast paced is the demand increase and are therefore not interested in solutions where the future infrastructure needs are not considered. For this reason WDM network planners require planning tools which ensure a functional system at its maximum capacity independently of the number of channels used at the time of deployment. Newly installed long haul transoceanic systems, for example, have now terabit per second maximum capacity though initially deployed channel capacity may just be a fraction of such value [1].

In other to accurately model the behavior of an optical network, and more specifically of the Erbium-Doped fiber Amplifier (EDFA) and Raman optical amplification, the WDM channels traffic matrix being propagated must be considered. Though the signals carried by WDM channels are obviously independent, their performances are not. There are both linear and non-linear inter-channel effects that damage the quality of the signals, such as the crosstalk [13], and the inter-channel cross-phase modulation (XPM). Hence the performance of an unchanged channel fluctuates when adding or dropping other WDM channels. In short, due to the optical amplification, real scenarios channels performances are inter dependent, however using an unusual simulating paradigm such inter dependency can be eliminated, at a certain cost.
Actually, it possible to guarantee system maximum capacity functionality with Real Amplification simulating methods, i.e. simulating methods that account for the signals entering the amplification network components. Yet, as in real scenarios, channels performance are susceptible of fluctuations. In this work a Planned Amplification simulating method presented, implemented and studied in terms of viability. It is intended to keep satisfying the WDM planner needs regarding maximum capacity system functionality while eliminating performance fluctuations.

II. OPTICAL NETWORK SIMULATORS THEORETICAL OVERVIEW

It is paramount to understand the behavior of a real system in order to emulate it. It is therefore convenient to discuss the real systems before advancing for the simulations. The target systems of the optical simulators described in this chapter are multi-haul Dense Wavelength Division Multiplexing (DWDM) transmission system, which are now capable of transmitting up to 128 channels per fiber pair [12]. Nowadays many DWDM systems feature single channels capacities of 100 GB/s rate, and state-of-art experiments achieve channel capacities higher than 400 GB [7] [11]. Nowadays systems are able to transparently add and drop individual channels in every optical multiplexing node (OMN), which can either be OADMs or RODAMs, depending on their components and architecture [8]. Two optical amplification types were conspired: EDFA [3] and Raman [10] amplification. In both types the gains are wavelength dependent. The amplification gains depend on the signals being amplified, and, deterministic gains impose the addition of noise to such signals [4]. Such gains can be modeled by a singly ordinary differential equation [2] [6].

It is favorable to divide WDM network simulators in four distinct modules: The network configuration, the optical multiplexing section (OMS) and routed channels definition, the simulating method and the performance calculations. Besides the simulating method, the stages are rather simple.

A. Network Configuration

The first step of configuring a network, is to set up the optical paths. This includes selecting the number and type of nodes, number and length of spans and / or for optical multiplexing sections. The nodes are divided in two groups, the optical multiplexing nodes and the optical line nodes (OLN), with the major difference between them being that line nodes are incapable of adding or dropping WDM channels. A span is regarded as a segment of fiber optic cabling connecting two nodes of which at least one is a line one, whereas an optical multiplexing section, connects two optical multiplexing nodes. This sections specifically connect the optical components which are responsible for multiplexing and demultiplexing the WDM channels, the Wavelength Selective Switches (WSSs) [9]. A single optical multiplexing section can thus contain several spans. Finally, an optical path is defined as the path connecting two optical multiplexing nodes which initialize and terminate one or more WDM channels. Optical paths at least one optical multiplexing section long. Notice that the same optical multiplexing section and /or node may belong to more than one Optical path.

B. Optical Multiplexing Section and Routed Channels Definition

The optical multiplexing section and routed channels definition stage of the simulator is, as well as the network configuration, independent of simulating method. Regarding the optical multiplexing section, the most important parameters are the maximum channel capacity (maximum number of WDM channel supported), the number of allowed different modulations and their types, and the full maximum capacity modulation type (MT) quotas. These quotas state how many channels of each available modulation type are expected in the optical multiplexing section. In a two modulation type scenario, i.e. in a optical multiplexing section that allows only two different modulation types, for example, quotas of 50% / 50% state that half of the wavelengths are expected to be occupied with channels with a certain modulation type and the other half with channels of the alternative modulation. Notice that these parameters, the optical multiplexing section ones, are defined before and independently of the routed WDM channels.

After configuring the optical multiplexing sections, routing channels is necessary. For each desired frequency, modulation types, data rates and target BERs are selected. The target BER is usually the same for all channels, however, respective modulation types and data rates may differ.

C. Real Amplification Simulating Method

The Advanced Real Amplification simulators take into account the currently routed channels and also occupies the non-used wavelengths with planned channels. Using this method, the WDM system is virtually working at its maximum capacity regardless of the maximum capacity percentage of routed channels.

When the routed channels are just a fraction of the system maximum capacity, the maximum capacity traffic matrix of the optical multiplexing sections in unknown. Thus the planned channels are distributed between the existing modulation type, in concordance with the maximum channel capacity modulation type quotas. The system makes an attempt to converge with the specified quotas, but such is not be possible if such quotas were already violated in the routed channel. Otherwise, regardless of the modulation type of the routed channels, the maximum capacity traffic matrix achieves the desired quotas between modulation types. Anyway, the resulting traffic configuration is used as one of the inputs of the Amplification components. Consequently, adding or dropping a WDM channel alter changes the amplification components parameters thus changing the performances of untouched channels.

D. Planned Amplification Simulating Method

For Planned Amplification simulating method, which is objective is to stabilize channel performance when adding
or dropping new WDM channels, the underlying strategy ensuring that the system is always virtually functioning at its maximum capacity is also by routing planned channels. However, to stabilize the performance of existing channels when adding or removing other real channels, one must stabilize the variables that induce the undesired fluctuation. The amplification components parameters must not depend on the routed channels, but rather on the planned ones, for those are invariable.

To accomplish such goal, the system will route and propagate two distinct full capacity traffic matrices throughout the network. The first one has no regard for the existing channels. All the system supported wavelengths are populated with planned channels, accordingly to the defined maximum capacity modulation type quotas. This traffic configuration is used to calculate the transfer functions of the components throughout the network, thus the quotas must be carefully chosen. Once computed, the transfer functions of amplification components are locked, preventing further re-computations of their parameters. The second routing traffic matrix is equivalent to the one achieved in the Real Amplification simulator, which considers the routed channels defined by the user. Since this traffic matrix has no impact on the amplifier component parameters, i.e. real channels are not used in the calculus of the transfer functions of locked components, adding or dropping channels has no impact on the performance of existing channels, regardless if the maximum capacity modulation type quotas are or not respected by the channels routed by the user.

N.B that this method trades stability for accuracy. By calculating the transfer functions based on planned channels rather than real ones, the Amplifiers transfer functions computations become less accurate, for some planned channels modulation types may misrepresent the actually routed channels ones. Furthermore, planned channels and real channels have intrinsic differences which are not related with modulation types. This simulation method deliberately fails to model a real system in order to stabilize channels performance.

III. OPTICAL SIMULATORS MODELS AND WORKFLOW

A. Real Amplification Implementation

Once the simulation method inputs are defined, the simulator possesses all needed information to perform its first task, which is, in the Real Amplification simulator, to route a maximum capacity traffic matrix based on real channels. In this simulating method, the routing function firstly allocates the chosen wavelengths to the respectively chosen channels, i.e. accordingly to the user channel configuration. Once that is finished, and only if the number of channels does not yet match the system’s channel capacity, planned channels are routed, accordingly to the defined modulation type quotas if there are more than one modulation types allowed. As the simulator exits this function, every optical multiplexing section traffic matrix is fully populated.

Contrasting with real channels, which naturally travel along the full length their optical path, the implemented planned channels are only one optical multiplexing section long, meaning they are added and dropped in every existing optical multiplexing node. Thus, when using the Real Amplification simulating method, even in situations where the real channel maximum capacity traffic matrix completely respects the determined modulation type quotas and frequencies, the performance of existing channels may still suffer variations when adding and dropping other channels.

Once a maximum capacity traffic matrix is routed, the necessary information to calculate the amplifiers parameters is known. Since the signal at the input of the amplification (EDFA and Raman amplification) components is one of the arguments of their transfer function, the computed parameters calculation depends on the fed traffic matrix. The amplifiers work towards achieving a certain gain and gain slope, however the system requested gains and gain slopes are not always obtained. In those situations, the amplifiers are regarded as in a saturation state. The amplifiers noise figure is dependent on such values. Along with the amplifier gain, the NF defines the generated amplified spontaneous emission (ASE) noise.

Once the amplifier parameters are calculated, the propagation function is used to propagate the signal throughout the network. It guarantees that the signals that arrive at the receivers are the correct ones, by applying and updating the appropriate component transfer functions to the channel signals which cross them.

B. Planned Amplification Implementation

The first task to be executed by the Planned Amplification simulating method is also to route a maximum capacity traffic matrix throughout the network. This time however, user defined channels are supposed to be neglected, therefore the routing function is called under the planned mode. The result of routing in such mode is a maximum capacity traffic matrix populated with planned channels only, in concordance with the defined modulation type quotas. Thus the actually routed channels are, at this point, irrelevant.

As happens in the Real Amplification method, after the routing the traffic matrixes, the simulator is ready to calculate the amplifiers parameters. Notice that this time, no real channels are routed thus no calculus depends on them. The calculated parameters depend only on the planned channels and respective quotas. Routing additional channels has no consequence on such quotas. Once the parameters are calculated, the amplifiers lock down.

Since the amplifiers are locked down, the channels selected by the user can effectively be routed. The achieved maximum capacity may (or not) have some planned channels, but the actual modulation type quotas may be different than the planned ones. Therefore, the following propagation may carry a different traffic matrix which would change the amplifiers parameters, however such values are not recalculated. While many transfer functions are updated during the propagation, amplifiers transfer functions are locked down, so their gains, gain slopes and NFs are not affected by real traffic. Each
channel gain is not only deterministic, but constant. Hence, channel performances depend only on its their characteristics.

C. WDM Channel Performance

The ultimate parameter regarding the system functionality is the channels’ (OSNR) System Margin.

\[ SM_{OSNR}(\lambda) = OSNR(\lambda) - Pen(\lambda) \quad (1) \]

The SM of a given channel is the difference between that channel obtained OSNR and its respective frequency experienced penalties (Pen). These penalties account for all optical effects that damage the quality of the signal.

IV. Simulation Scenarios

Several configuration parameters were made constant throughout the simulations, such as the optical multiplexing section ones. The defined maximum capacity was 96 channels and a total of two distinct modulation types were allowed. For such channel capacity the used band is the C Band (corresponds to the amplification range of the EDFA) featuring frequencies from 191.35 to 196.1 THz, meaning a channel spacing of 50 GHz is employed. One of the modulation types regards 100 GB/s channels, the other 40 GB/s ones. The defined maximum capacity modulation type quotas were 50%-50%, meaning that the Planned Amplification planned channels traffic matrix had 48 channels of each modulation type. Different span optical multiplexing section input powers were assigned to each available modulation type.

Since it is the main analyzes goal to quantify error that the Planned Amplification simulating method introduces, worst case scenarios must be tested. Hence it is necessary to feed the systems with routed channels that violate the planned quotas. That way, the inputs for the amplifiers parameters calculus between simulation methods will differ, thus so will the achieved gains and NFs and consequently the overall channel performances. Figure 1 illustrates the differences of between the maximum capacity traffic configurations that were used in such computations for Real and Planned Amplification simulating methods. Notice that in some configurations only the modulation type frequencies change between traffic matrixes (constant power configurations, C), while in other configurations the modulation type planned and real quotas themselves are different (variable power configurations, V).

The simulators using the two simulating methods were used in the same networks so their results could be compared. On one hand there were the test links, which are point-to-point links with maximized reachability under different premises. The short haul test link was limited in terms of maximum number of optical multiplexing sections and spas, 1 and 3 respectively. The long haul test link is also one optical multiplexing section long only, but is limited in terms of span loss instead of span number. Finally, the metro test link is also limited on span loss (with a much lower value) but not on the number of optical multiplexing sections. Table I presents the obtain parameters for such maximization process. (The short and long haul test links were simulated with and without Raman Amplification (R) of which parameters are dependent).

On the other hand there was a mesh network, simulating a real network scenario. Contrasting with the test links, this network is very heterogeneous. Besides the optical multiplexing nodes having different architectures, the optical multiplexing sections have different total lengths, span number and lengths, input powers, maximum allowed number of channels, number of allowed modulation types and respective modulations, maximum channel capacity modulation type planned quotas and fiber type segments. The physical topology of such network is presented in figure 2.

V. Results

For each simulated network, the channel performances of all channels were compared in order to quantify the maximum channel (ONSR) System Margin error between simulating methods. Such errors are a direct consequence of the discrepancy of the to achieved ONSRs and Pen between methods.
Regarding the OSNR, the obtained differences arose from differences in the ASE noise power, $P_{ase}(\phi)$. In short, the amplifiers gain causes the signal power at the receiver to be as high as necessary (and the necessary signal power at the receiver is naturally the same among simulating methods). However, the signal power at the amplifiers input is different between methods and thus so are the necessary amplifier gains and consequent NF. Thus, the ASE noise power reaching the receivers is not the same between modulations, as such differences are noticeable on the obtained channel OSNRs.

As far as the Pen goes, besides the non-linear penalties, the differences are negligible. The non-linear penalties, $Pen_{NL}$, depend on the signal and noise power and modulation type, values which are different between modulations type groups.

The maximum error values between methods presented bellow were obtained when the link was feed with the variable power real traffic channel configuration presented in figure 1.

As far as the short haul link is concerned, the maximum SM error obtained between simulations was 0.836 dB. Achieved OSNR differences between methods were the main contributor for such error. When using Raman amplification the spans length increased, however gain and power slope responsibilities were divided between Raman and EDFA. Thus, the maximum SM error between methods, also again due to achieved OSNR differences, was merely 0.643 dB. It was proven that when EDFA are forced to work under saturation states, which they were without the Raman amplification, the obtained error were higher. A short haul link with no Raman amplification but with a span length of 125 km instead of 150 resulted in lowering the measured error. $Pen_{NL}$ contributions to the overall errors between methods were negligible for the short haul link.

The long haul link registered comparable contributions between OSNR and $Pen_{NL}$ method differences. The maximum registered error was 0.911 dB, for the link without Raman Amplification. The $Pen_{NL}$ differences were proven to be connected to the number of optical multiplexing sections and spans of the optical path. The maximum registered error for a long haul link variation featuring 2 optical multiplexing sections instead of one was 0.300 due to a much lower $Pen_{NL}$ difference between methods.

The metro link featured short spans and plenty multiplexing sections, thus both OSNR and $Pen_{NL}$ differences were expected to be low, and they were. The maximum registered error between simulating methods was 0.103 dB. The utility of this test link was to conclude that real and planned channels inherent differences could be overlook. The 19 optical multiplexing sections maximized the differences between channel types and simulations with each the real and planned maximum capacity traffic matrixes were the same (so that all measured error was solely due to channel type conceptual differences) were executed. The obtain error was 0.003 dB, so channel type differences were concluded not to be a problem for the Planned Amplification simulating method.

Figure 3 presents the obtained channels System Margins error between simulating methods for the mesh network presented in figure 2.

As expected, all the obtain differences are within the maximum and minimum System Margin difference range registered in the test links. This was expected because neither real and planned configurations used in amplifiers parameters calculation are as different in here as they were in the test links nor the EDFA components are as stressed as they previously were. Furthermore, the longest optical multiplexing sections was also not as long as the ones featuring the long haul link.

The blue optical path channels were those which presented the highest error between simulating methods. The blue optical path contains exactly the three optical multiplexing sections where the differences between real and planned channel configurations are higher, thus such result was not surprising. The SM differences were mainly originated by differences in the OSNR and therefore all negative.

The rest of the optical paths contain optical multiplexing sections belonging to the bottleneck, where real and planned full capacity configurations are very different, and optical multiplexing sections not belonging to the bottleneck, such configurations are not so different or are even equal. The orange optical path, being the shortest of these three, also presents the most negative SM, because still no significant $Pen_{NL}$ differences are registered. The green green channels present sightly more significant $Pen_{NL}$ differences, which decreased the error between modulations. In the red optical path, the longest of the paths, the channels SM difference oscillates between negative and positive values, for the OSNR and $Pen_{NL}$ contribution to the channel performances error is comparable.

VI. CONCLUSIONS

The test link analyses culminated in the exposure of the differences in the noise power at the receiver and in the non-linear penalties between simulators. These differences combined are responsible for the overall registered channel performance errors. The causes for worrisome differentials were identified as being EDFA components working in saturation states and very long optical multiplexing sections. Since the highest channel performance error between simulating methods of 0.911 dB, it is safe to say that employing a planned method penalty of 1 dB, the Planned Amplification simulating method could be used regardless of the network, optical multiplexing
section and channel configuration, however, it is a costly price to be paid.

As far as the mesh network is concerned, the maximum absolute error registered in channels performance was 0.096 dB. All the obtained difference values (System Margins, OSNRs, penalties, gains, gain slopes and noise figures) lower difference values obtained from point-to-point maximum reach test links. Furthermore, for most of the channels, the Planned Amplification method channels performance were, as expected, lower than Real Amplification method ones, which is not as worrisome as the opposite. Even though the network was chosen to maximize the channels performance error between simulating methods, the obtained channels performance errors are much lower than the ones previously registered. These results were very satisfying as they prove that the Planned Amplification simulator is one track to become a viable WDM network planning solution.

REFERENCES


