Routing in medium term optical networks in ICT STRONGEST

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Abstract: In Wavelength Switched Optical Networks (WSONs) with dynamic path establishment and wavelength assignment, connection requests between a source and a destination node are negotiated at lightpath connection set up, where a specific wavelength is assigned for data transportation among the two nodes that may span multiple links. In order to guarantee QoS in such networks Wavelength Routing Algorithms should be appropriately developed to ensure minimum blocking while physical layer performance is guaranteed for all established lightpaths. The latter is guaranteed with the introduction of appropriate Physical Layer Impairment awareness in the path establishment procedure. Furthermore the routing engine should be able to address the issue of network availability which, in turn, requires efficient resilience mechanisms. In this paper we present the routing strategies developed in the framework of ICT STRONGEST project, suitable for dynamic optical networks during planning and operation of such networks.

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Keywords: optical networks, wavelength routing algorithms.

1. Introduction

Current advances in access networks postulate user rates ranging from 100 Mbit/s to 1 Gbit/s. When the overall traffic is funneled back in the Core, there will be a tremendous increase in traffic volume that will range to Pbit/s leading to a network with a dynamic behavior characterized from traffic patterns with high spatial and temporal asymmetry. Moreover, since Core and Metro networks will be the essential infrastructure to support existing and future Internet services, this traffic should be transported between two access networks under certain Quality of Service (QoS) guarantees. While the traffic growth can be accommodated by exploiting the capacity of WDM systems, the available fiber and wavelength resources will not be able to serve the constantly increasing demand unless the resources are utilized and reserved in an efficient manner. Hence for the sustainability of the Future Internet, the end-to-end QoS guaranteed performance is of paramount importance. QoS in any network can be only served when primarily the issues of throughput, call blocking, resource utilization, physical performance and availability have been optimized. Then QoS can be applied based on classification of different flows, as in a GMPLS controlled network, according the service priority classes and/or based on service attributes which will be taken into account when routing these flows in the network.

In ICT STRONGEST, Wavelength Switched Optical Networks (WSONs) are discussed among the medium term networking scenarios that can achieve those QoS parameters simultaneously. Here connection requests between a source and a destination node are negotiated at lightpath connection set up, where a specific wavelength is assigned for data transportation among the two nodes that may span multiple links. Wavelength routing algorithms (WRAs) are necessary for path computation and lightpath assignment. They should serve the initial goal of minimizing blocking and maximizing resource utilization while accounting for Physical Layer Impairments (PLI) and address the appropriate resilience mechanisms. In that way WRA in an optical network should efficiently arbitrate lightpath establishment while simultaneously guaranteeing adequate physical performance.

The above task however becomes especially complicated when WSONs are concerned, where either the physical layer that has been designed to operate as 'static' and now is part of a network architecture where it should serve requests with dynamic lightpath set-up and tear-down or *traditional* shortest-path based routing and connection establishment procedures that have been developed for non-optical networks may not guarantee optimum operation, as far as both physical and network performance is concerned.

In this work we emphasize on the fact that routing and resilience should be strategies defined both in the planning stage of an optical network that has an outlook towards dynamic operation, and in the operation stage of such a network. Having this in mind we debate that the performance of WRA based only on lightpath length are unsuitable for WSON networks. Having established that a routing algorithm that adapts to the "dynamic" network characteristics is more suitable, we exemplify with specific case studies of network planning and operation. Simultaneously we discuss efficient network resilience mechanisms that are necessary to achieve the goal of QoS guarantees.

2. Routing in medium term optical networks

Physical layer impairment routing has been an issue of research for several years. Transmission in fibers causes various degradations that accumulate along a fiber path and among different wavelengths. Thus, the need for Wavelength Routing Algorithms (WRA) that account for Physical Layer Impairments (PLIs) has emerged to guarantee physical performance. Up to date, PLI aware WRAs have been proposed [1]-[7] as means to ensure adequate physical layer performance in dynamic optical networks with no predefined paths between source and destination nodes. Most of the work that appears in the literature either emphasize the modeling of PLIs (e.g. [2]-[4]) by analytical or numerical means or suggest modifications to algorithms in order to include PLIs (e.g. [5]-[6]). Recently, some work has been presented in the deployment of the PLI aware routing into realistic environments [7].

Meanwhile, introducing PLI awareness into routing does not mean that impairments are overcome. Regeneration at optical nodes has been proposed as means to relax physical degradation by reducing impairment accumulation in an optical path. Optical 2R regeneration is a viable solution based on a number of alternative configurations, however this does not necessary imply that it regenerates perfectly the impaired optical signal. On the contrary, optical regeneration allows only fraction of the accumulated noise to be conveyed via concatenated optical nodes [8].

In ICT STRONGEST we have developed a view that the PLI aware routing engine of an optical network should provide a trade-off between accuracy and speed as fast network reconfiguration and high data rates impose constraints on both path computation and restoration times. Although in the planning phase of the network this may not seem as an important issue it becomes significant when considering resilience mechanisms where secondary paths may be longer than shortest-path routed primary paths, PLIs might set additional limits precluding the identification of an alternative path or creating additional delays.

Furthermore in ICT STRONGEST we have concluded that path establishment based on the path distance that has been traditionally used in WSON networks is not efficient especially when PLIs are considerable, by failing to guarantee suitable physical performance. Novel algorithms based on physical layer performance characteristics that exhibit resource availability awareness (e.g. occupancy etc) can achieve an excellent resource management while guaranteeing QoS.

Finally, in order to enhance network availability in ICT STRONGEST we investigated various strategies that combine the main benefits of the well-established mechanisms, i.e. low recovery time, high guarantee of traffic restoration and low network resource consumption. The developed routing engines incorporate the possibility for 1:N dynamic protection, restoration and protection re-planning (i.e. optimal backup paths are re-calculated periodically).

3. Physical Layer Modelling

The physical layer of the optical network under investigation is considered as a set of Wavelength Division Multiplexing (WDM) transmission systems that are interconnected by optical nodes (Reconfigurable Optical Add/Drop Multiplexers – ROADMs). The fiber links comprise fully dispersion compensated fiber spans with single mode fiber (SMF) segments followed by dispersion compensating fiber (DCF) segments, like in [9]. Span losses and terminal losses are exactly compensated by an Erbium Doped Fiber Amplifier (EDFA) at the end of each span (span EDFA) or after the WDM terminal (booster EDFA) or before the receiver terminal (pre-amplifier EDFA). The impact of the intermediate ROADMs is considered negligible unless regeneration is considered, as described below.

Regarding the modulation formats of the WDM systems different views have been investigated according to the bit rate and reach trade off. Optical communication systems with 10Gb/sec channel bit rate have predominantly used NRZ as a modulation format. With data rates moving to 40Gb/sec, dispersion in the fiber limits the distance over which the data can be transmitted and differential phase modulation (e.g. DQPSK) formats have been suggested as alternatives. As the scope of this work is limited to medium term optical network scenarios we have assumed two different cases of modulation formats corresponding to the bit rate per channel. If the bit rate per channel is 10Gb/sec the well studied NRZ modulation format is assumed while for 40Gb/sec advanced phase modulation formats like DQPSK are considered [10]. It should be noted here that the two different cases correspond to different physical layer modeling as the significance of these impairments vary.

Physical Layer modeling of NRZ- WDM systems with and without regenerators

In the case of transmission through just a single link, the impact on the signal can be modeled analytically via Q-factor degradation. The Q-factor of the signal after being transmitted over one link for example is given by:

$$Q \approx RP_{s,M} / [\sigma_0 + \sigma_1] \quad (1)$$

where $\sigma_0 = \sqrt{\sigma_{th}^2 + 2qRP_{ASE,M}^{ch} + \sigma_{spon-spon}^2}$

$$\sigma_1 = \sqrt{\sigma_{th}^2 + \sigma_{shot}^2 + \sigma_{sig-spon}^2 + \sigma_{sXPM}^2 + \sigma_{spon-spon}^2 + \sigma_{FWM}^2}$$

R is the responsiveness of the terminal receiver, σ_{th} is the thermal and σ_{shot} is the shot noise of the receiver. The Amplified Spontaneous Emission (ASE) related spontaneous - spontaneous $\sigma_{spon-spon}$ noise and signal - spontaneous $\sigma_{sign-spon}$ noise are calculated as in [9] for the whole amplifier chain. σ_{XPM} and σ_{FWM} are the standard deviations of the cross-phase modulation (XPM) and four-wave mixing (FWM) generated fluctuations respectively. ASE and XPM/FWM related noise factors are considered transmission related impairments and can be accounted for in a single noise term, σ_{imp} both in σ_o and in σ_1 (e.g. $\sigma_{1,imp}{}^2 = \sigma_{spon\text{-}spon}{}^2 + \sigma_{sign\text{-}spon}{}^2 + \sigma_{XPM}{}^2 + \sigma_{FWM}{}^2$ and $\sigma_{o,imp}{}^2 = \sigma_{spon\text{-}spon}{}^2$).

If optical nodes incorporate regenerators then error accumulation should be introduced in the modelling, hence the bit-error rate (BER) should be used as a metric of the physical performance. Once the signal reaches such a node, the transmission induced noise σ_{imp} is reduced. In order to understand the noise re-distribution through a regenerator we borrow the method from [8] that is describing the evolution of noise in a linear amplifier or a 2R regenerator which is characterized by the parameter γ. The value of γ characterizes the ability of the device to reduce the noise of the signal. The difference between BER calculations in a multi-link path with regeneration is different than a non-regenerated path that is discussed in [11]. In the case where regenerators are deployed, in order to have a realistic estimation of the path BER one should account for the BER after each link.

Physical Layer modeling of DQPSK- WDM systems

For the DQPSK systems on the other hand we assume that Optical Signal to Noise Ratio performance estimation together with PMD performance may be adequate to describe their physical performance [10]. Non-linear physical effects such as XPM and FWM are implicitly considered by adding an extra small margin in the target OSNR.

In order to calculate that we assume that the signal power at the output of the receiver is $P_{pre-amplifier\_output\_signal}$. The ASE generated in an amplifier is obtained by $P_{ASE\_amplifier} = h \cdot B_0 \cdot f_{central} \cdot (g-1)$ where parameter h is the Planck constant, B_0 is the amplifier optical bandwidth, $f_{central}$ is the central frequency of the lightpath and g is the amplifier gain. The noise power at the output of the pre-amplifier can be calculated by the next expression:

$$P_{ASE\_pre-amplifier\_output} = P_{ASE\_booster} + (2 \cdot P_{ASE\_DCF}) \cdot (N_{spans} - 1) + P_{ASE\_pre-amplifier}$$

Therefore, the OSNR at the end of a path can be calculated as:

$$OSNR_{end\_of\_path} = \frac{P_{pre-amplifier\_output\_signal}}{P_{ASE\_pre-amplifier\_output}}$$

The simulation tool uses this expression to compute the path OSNR that depends on the number of traversed fiber spans. Subsequently, it is checked whether it fulfills the minimum OSNR requirements, defined by a pre-defined threshold shown in Table 1. In addition, the feasibility of the path is checked in terms of total PMD accumulated along the path:

$$DGD = D_{PMD} \cdot \sqrt{L} \text{ [ps]}$$

Again, a maximum threshold is pre-defined (cf. Table 1).

Table 1 – PMD and OSNR thresholds

DQPSK - 25 spans	*PMD threshold [ps]*	*OSNR threshold [dB]*
40Gbps	*6*	*12,5*

4. Planning phase of optical networks

Physical Layer Impairment aware – 'k' Shortest Path algorithm (IA-kSP)

The suggested routing scheme consists of a heuristic physical layer impairment-aware dynamic routing and wavelength assignment using a constraint shortest path (CSP) method for path computation. A 'k-shortest path' routing technique is used with restrictions based on PLIs. As additional improvement, those links that overcome their maximum capacity are avoided in the path computation. For each incoming traffic connection request, a list of 'k' shortest paths is calculated. For each one of them, the physical constraints are checked, verifying whether they fulfill the minimum OSNR and the maximum PMD thresholds. An available wavelength along the feasible path is searched using the 'first-fit' algorithm. If both a feasible path and an available lambda are found, a lightpath is established along the corresponding path links. If not, this process is repeated for the next path in the list of 'k' shortest paths. If none of the 'k' routes is feasible or there is no available lambda for any of the feasible paths, the traffic request is rejected.
We propose a dynamic cost function with variable weights for the link OSNR and the link load. The total cost function per link thus considers both the OSNR influence and the link load:

$$total\_cost = weight_{OSNR} \cdot cost_{OSNR} + weight_{load} \cdot cost_{load}$$

$$weight_{OSNR} + weight_{load} = 1$$

$$0 \leq weight_{OSNR} \leq 1$$

$$0 \leq weight_{load} \leq 1$$

Adapting this cost function to the network topology, traffic type and other transmission characteristics, it is possible to improve the network performance or extend the lifetime of the network. In our case, the used values for the parameters $weight_{OSNR}$ and $weight_{load}$ of the link cost function are 0.5. Others pairs of values were applied but no performance improvements have been found, hence are not shown here.

Case study: TID with 40Gb/sec DQPSK WDM transmission system

The network topology considered in this study is the TID network [12]. We have assumed that the predicted traffic demand for years 2012 and 2015 are 235 and 512 optical circuits respectively (i.e. an increase of 50% per year approximately). We assume 40Gbps connection requests. To account for the OSNR we assume 80km fiber spans and the link amplifiers have 18dB gain and a noise figure of 5dB while the booster amplifier gain is 16dB and the noise figure is 5dB. Terminal equipment are considered with 3dB losses and the attenuation of SMF fiber is equal to 0.35dB/km while of the DCF fiber 0.5dB/Km.
A shortest path (SP) routing technique is compared to the proposed heuristic, i.e. IA-kSP, for different value of the parameter 'k' (i.e. 2, 3, 4, 5 and 10). The results for 2012 and 2015 are presented in Figure 1.

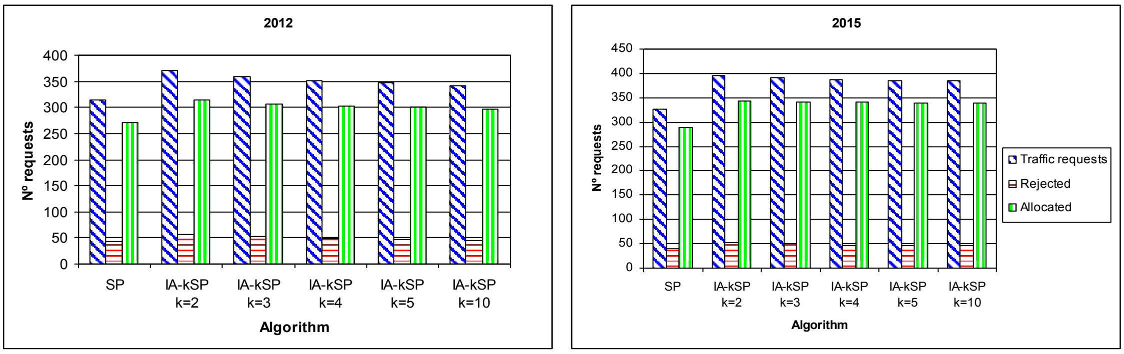

Figure 1 – SP vs. IA-kSP in terms of allocated and rejected traffic requests when the number of circuits through the most loaded link reaches 80 (Left: 2012 – Right: 2015)

IA-kSP heuristic allows allocating a higher number of traffic requests before reaching the 80 channel limit in any of the optical links. Therefore, the deployment of new fibers is postponed with respect to the SP algorithm. Regarding the influence of the parameter 'k', originally it could be thought that a greater value of 'k' implies a higher number of connections through the network links. Nevertheless, a higher 'k' also represents longer paths. So, the physical constraints force the rejection of these long paths. It can be observed that a value of 2 for the parameter 'k' is enough to obtain the best results (15% of improvement in 2012 and 20% in 2015, compared with SP), that is, calculating the two shortest paths for each traffic request allows distributing the traffic load along the network links while the physical constraints are conveniently overcome.

5. Operation phase of optical networks

Impairment aware – S-1/Q algorithm

We utilize the routing engine of [9], expanded with respect to the modelling of the physical layer, the routing algorithms and the inclusion of resilience mechanisms. In order to investigate the effect of routing and keep the problem formulation linear and solvable using a variant of the constrained shortest path (CSP) family of algorithms that exhibit exceptional runtime suitability and resource availability awareness for dynamic environments, we resort to a heuristic [11]. Here we assume as a weight option is the estimated 1/Q of the wavelengths of a particular link in isolation. In other words, if we isolate the link by keeping the original wavelength occupation, we estimate the 1/Q quantity of each available wavelength. This weight can be viewed as a more comprehensive estimate of the impairment profile of the available wavelengths on a link. The derived heuristic is called constrained S-1/Q. For comparison reasons we also formulate our heuristic when the cost is selected to be the distance of the path here called shortest distance (S-D) heuristic. In both cases the feasibility of a candidate lightpath is related to the BER of the signal under consideration.

Case study: TID with 10Gb/sec NRZ WDM transmission system

For our studies we assume a WDM system with 50 GHz channel spacing and the power per channel $P_{S,\,M}$ is equal to 3 mW unless otherwise stated while all other physical parameters are similar to [9], while the BER threshold is set to 10^{-12}. We have calculated the blocking probability with respect to the increase in connection requests. The applicability of the approach is more evident in the low blocking region where S-1/Q outperforms S-D by an order of magnitude but still remain orders of magnitude worse with respect to the PLI blind case. The introduction of the suggested algorithms has a larger impact in the converted networks. Here S-1/Q is performing similarly to the reference S-D when no PLIs are accounted for. Specifically S-1/Q outperforms the PLI-aware S-D by three orders of magnitude.

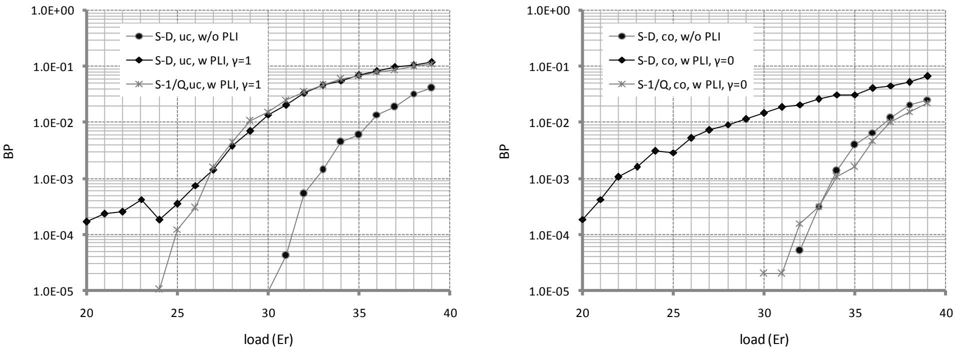

Figure2 – BP performance (a) for the converted network (γ=0) and (b) for the unconverted network (γ=1) with respect to the offered traffic load.

The difference on the way these algorithms behave with respect to blocking due to physical impairments is twofold: (i) the S-1/Q algorithm is inherently achieving load balancing across the network and within links. Hence interference to the already established lightpaths is minimized. (ii) by seeking solutions with good performance, S-1/Q leaves some margin for further deterioration. This means that if a number of lightpaths have already a BER that is far below 10^{-12}, then the establishment of even a large number of new lightpaths will not deteriorate their BER significantly.

6. Conclusions

In ICT STRONGEST, different optical networking scenarios have been benchmarked with respect to their QoS guarantee capabilities for mid term and future networks. Among the candidates for medium term networking scenarios, WSONs have been proven beneficial. A routing engine that is necessary for path computation and lightpath assignment should be able to minimize call blocking while guaranteeing adequate physical layer performance. In this paper we presented the developed mechanisms in ICT STRONGEST that can serve routing WSON networks during planning and operation. Because of the nature of those networks the routing engine deploys suitable algorithms that base the path establishment procedure on dynamic network characteristics (e.g. load, occupancy etc).

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