Abstract— A physical layer impairment aware wavelength routing algorithm is developed that accounts for Optical Signal to Noise Ratio (OSNR) degradation, Four-Wave Mixing and Cross Phase Modulation through analytical rules. The routing engine blocks connections that would be served by lightpaths with insufficient Q-factor. Likewise, a connection that would cause the Q-factor of existing lightpaths to degrade beyond an acceptable threshold is also blocked. This engine can select among two path establishment algorithms depending on the considered cost, which can be either shortest path or shortest widest path. Three wavelength assignment algorithms (best fit, random fit and first fit) are studied and benchmarked.

I. INTRODUCTION

Core Wavelength Division Multiplexing (WDM) networks are envisaged to evolve from simple point-to-point links to intelligent, optical networks. The latter should be preferably transparent while transportation from a source node to the proper recipient node should be completed in a reliable and efficient manner. This means that both physical layer that conducts transmission and routing algorithms that coordinate transportation should be designed appropriately [1]-[4].

In transparent optical networks, transmission imposes various impairments that accumulate nonlinearly along a fibre link and thus traditional routing algorithms cannot always guarantee optimum operation as far as both physical and network performance is concerned. A Wavelength Routing Algorithm (WRA) might be very efficient in finding a particular shortest lightpath to interconnect two nodes in a meshed network, minimizing in such a way the network resources utilized. The specific route however might impose unacceptable impairments to the signal. At the same time, due to the nature of the nonlinearities, inserting this lightpath may be detrimental for the physical performance of the existing ones.

From early on, it has been suggested that the WRA should account for Physical Layer Impairments (PLI) [5]-[8]. In [5] routing is performed by using pre-calculated routes considering only four-wave mixing (FWM). In contrast, [6] takes into account all transmission effects, which are estimated based on extrapolations from numerical simulations. [7] presents a set of guidelines for routing wavelengths, modeling all effects as a single noise figure under worst case assumptions. None of these has considered the effect of the path establishment algorithm, as they all use the shortest path one.

In this paper, the routing engine of [8] is used and the proposed method is based on investigating Optical Signal to Noise (OSNR) degradation and two main cross-channel transmission impairments, FWM and cross phase modulation (XPM) through analytical models [8]. Here two path establishment algorithms and three wavelength assignment algorithms are investigated with respect to the network blocking performance. It is expected that since signal degradation due to the nonlinearities, and hence PLIs, are related to the fibre occupancy and the path length, the path establishment algorithm may play a crucial role in a PLI aware routing engine.

II. ROUTING ENGINE

In wavelength routed optical networks, lightpaths are circuit switched optical connections. They are defined as a number of links between a source-destination pair of nodes, through all the intermediate nodes with a wavelength assigned on each link [1]. Path establishment in optical networks is the procedure of path selection among the available paths and takes place in a dynamic network before establishing a lightpath [1]. There might be possible to attain more than one continuous wavelength to support a specific lightpath and assigning a specific one from a set of candidates is a separate issue. Hence wavelength routing commences with a connection request to conclude with lightpath establishment between the nodes in question. Here dynamic connection requests are assumed [7]. Only one type of service is considered, with constant lifetime of 4 time units. The inter-arrival times of the connection requests follow a Poisson distribution with an average inter-arrival of 10 time units. Furthermore connection requests happen randomly and do not follow any specific traffic matrix.

The flowchart of the algorithm is shown in Fig. 1. For path establishment the engine can choose to base the decision either on ‘shortest-path’ SP routing algorithm or on the
shortest widest path’ SWP algorithm both implemented by
the Bellman-Ford algorithm [9]. For the first case, when a
request for connecting any two nodes appears, the shortest
path is calculated. SWP seeks the path that has maximum
continuous (adjacent) available wavelengths and thus is
least congested. This multi-criteria algorithm operates as
follows: It first checks all the possible L wavelengths and
returns a table of available continuous ones that can connect
the two nodes together with possible corresponding
lightpaths that hold the lowest cost as defined by the first
step. The PLI calculation is either turned on (PLI aware) or
off (PLI blind). In the first case the Q-factors of the
potential lightpaths are calculated and compared with a
threshold value $Q_A$. Lightpaths that fail this comparison are
dropped and are no longer considered candidate. Before
assigning a specific lightpath a final check is performed.
The system is probed consecutively with each of the
candidate lightpaths and investigates the Q-factor of the
connected lightpaths while comparing it with threshold $Q_B$. All candidate lightpaths that affect irreversibly the existing
connections are dropped and the final list of potential
lightpaths is formed. From the pool of candidate lightpaths,
one is chosen with the assistance of the wavelength
assignment algorithm. This means that it can be chosen randomly (random fit-RF-algorithm), by order of
numbering (first fit-BF) or by cost optimisation (best fit or-
BF). In the latter case, the cost to be optimised can be the
one defined at the beginning or a separate one [1].

![Routing Engine](image_url)

To evaluate the second (comparison with $Q_A$) and third
(comparison with $Q_B$) constraints, an analytical model is
used that provides a good trade-off between accuracy and
flexibility [6]. For its implementation, the physical layer is
regarded a set of K fibre links between the N nodes. These
links comprise 40 km single mode fibre spans each being
fully dispersion compensated by 8 km dispersion compensating fibre with other parameters as in [8]. The
cross-channel impairments that are considered here are
XPM and FWM. To calculate the Q-factor of channel $n$ after
M spans, the receiver is modeled with values typical for a
10 Gb/sec system with channels that have 50 GHz spacing
and the input signal power is +1dBm [6]:

$$Q(n) = \frac{RP_{\text{M}}}{\sigma_0 + \sigma_1}$$

(1)

where

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

(2)

and

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

(3)

Where $\sigma_{\text{th}}$ is the thermal noise of the receiver, $\sigma_{\text{shot}}$ is the
shot noise. The ASE related noise spontaneous -
spontaneous and signal - spontaneous $\sigma_{\text{spont-spon}}$ and $\sigma_{\text{spont-spon}}$ are calculated as in [10] for the whole span of amplifiers.
The total XPM-induced crosstalk on one channel due to
another is obtained by adding up the contributions from all
fibre sections and is given by [11] as the standard deviation
of the fluctuation at the receiver. In [12] the standard deviation $\sigma_{\text{FWM}}$ of the fluctuation stemming from FWM in a
chain of fibres and amplifiers, modified to include both
DCF and SPF fibres.

The Pan-European Network, the graph of which is defined
in [9] is used here as reference network has K=16 nodes
and N=23 links. It is assumed to be uniform with each fibre
section consisting of the Bellman-Ford [9], for the first case, when a
request for connecting any two nodes appears, the shortest
available path. Nonlinearities and ASE noise
accumulation depend on the length of the path so
minimising this length results in better physical
performance.

Starting with the SP algorithm combined with FF we use the
engine of Fig. 1 and ‘measure’ Q-factors of the
lightpaths as the traffic load grows from 5 to 30, with the
result shown in Fig. 2 (a). Evidently, a significant
percentage of existing lightpaths have a Q-factor less than
12. Apparently, Q-factors become worse as the traffic load
increases due to the effect of fiber nonlinearities. In this
case a PLI aware WRA is an asset since network resources
are not wasted. In contrast, as shown in Fig. 2 (b), a better
physical performance is attained when BF is used. There for
a scale factor of 5 only few channels exhibit Q-factor less than 10. SP combined with BF is actually giving back the
shortest available path. Nonlinearities and ASE noise
accumulation depend on the length of the path so
minimising this length results in better physical
performance.
A major conclusion from the results is that the BF algorithm outperforms the others with RF having the worst performance. This is important especially when Q_A=0. When PLI is turned on differences are smoothened out. In this case, all algorithms behave similarly as far as BP is concerned. The difference between the wavelength assignment algorithms is mainly reflected to how efficiently the choice is made among the set of available lightpaths. This set is now limited by PLI constraints and the effect of the assignment algorithm on the network performance is diminished.

For the diagram of Fig. 4 the routing engine of Fig. 1 is used for different costs (path length or congestion) and threshold values of Q_A. For the PLI blind case (Q_A=0) the SP algorithm allows a fine blocking performance. When Q_A≠0 and traffic load is low (scaling factor up to ~3), cross-channel nonlinearities do not deteriorate significantly the physical performance of the lightpaths or even when they do an alternative route through the network can be
found. Hence, BP is similar for the case of $Q_A=10$ and for the PLI blind case. When the offered traffic load grows, fibre links start getting populated and nonlinearities start affecting a high percentage of the lightpaths, as also illustrated in Fig. 2. Not all connections can established under the constraints and are blocked when $Q_A \neq 0$. For high traffic loads, blocking is increased by the exhaustion of network resources. As traffic grows, nonlinearities grow and SWP performs better as its inherent characteristic to find the least occupied link helps by relieving the blocking performance. The Q-factor depends on many parameters, for example the number of channels, channel spacing, fiber type and characteristics (dispersion, attenuation, nonlinearity), bit-rate, power etc. Evidently, each of these parameters can be used as an optimization variable in order to assess its impact on performance degradation, at system and consequently at network level. This is clearly manifested in Fig. 5. There, the BP is calculated for different values of power per channel. The Q factor of the lightpaths is affected directly by the power of each channel, through ASE and nonlinearities, and the blocking is increased for lower values of the Q factor. Such a curve can be used to collectively evaluate the impact of the power per channel on the network and physical performance, as well as to evaluate the impact of the path establishment algorithm. Note that for the PLI blind case, the BP is 0.01. A major conclusion from the above is that the decision on the type of WRA to be used on the network for specific traffic directly depends on the physical layer plant and vice versa.

### Optimization

The Q-factor depends on many parameters, for example the number of channels, channel spacing, fiber type and characteristics (dispersion, attenuation, nonlinearity), bit-rate, power etc. Evidently, each of these parameters can be used as an optimization variable in order to assess its impact on performance degradation, at system and consequently at network level. This is clearly manifested in Fig. 5. There, the BP is calculated for different values of power per channel. The Q factor of the lightpaths is affected directly by the power of each channel, through ASE and nonlinearities, and the blocking is increased for lower values of the Q factor. Such a curve can be used to collectively evaluate the impact of the power per channel on the network and physical performance, as well as to evaluate the impact of the path establishment algorithm. Note that for the PLI blind case, the BP is 0.01. A major conclusion from the above is that the decision on the type of WRA to be used on the network for specific traffic directly depends on the physical layer plant and vice versa.

![BP versus power per channel when PLI aware routing algorithm is performed for SP and SWP.](image)

Comparing the two algorithms the number of steps performed should be discussed. For the specific network the SP algorithm used $L^*O(K^2) + M$ while the SWP algorithm $O(K^2) + M$, where $M$ is the number of existing affected lightpaths which may be a maximum of $L^*N$. The first factor $L^*O(K^2)$ stems from the fact that the shortest path algorithm is searching all wavelengths for their shortest path. For the SWP algorithm however this is not the case and it is obvious that SWP is much more efficient in terms of algorithm steps.

## CONCLUSIONS

A PLI aware WRA algorithm has been used that has a choice of two algorithms to perform the path establishment. The SP algorithm does not consider at all the occupancy of a link that is directly related to the cross-channel effects of the nonlinearities. So although they are both efficient as far as blocking performance is concerned the second manages to indirectly minimise PLI, for the PLI blind case. Therefore, good physical performance is ensured with the SWP algorithm even when no PLI constraints are considered.

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## REFERENCES