Optimization of survivable optical networks in the presence of physical layer impairments

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Abstract

The physical layer impairments (PLI) incurred by optical transmission media in optical networks accumulate along the optical path, which affects the performance of the optical networks. To efficiently design the optical transparent network, it is important to compute feasible routes and wavelengths in the presence of PLI to guarantee that the optical signal will reach the receiver with desirable signal quality. Optimization strategies were investigated to plan and operate the optical transparent network towards enabling ($\geq$ 100 Gbps) transmission within a fixed grid of 50GHz channel. This project reviews technological options for optical-path computations in the presence of PLI, considering the distinct wavelength and wavelength continuity constraints.

Keywords: transparent optical network, routing and wavelength assignment (RWA), physical layer impairments (PLI), reconfigurable optical add-drop multiplexer (ROADM), survivability, Optical Signal to Noise Ratio (OSNR)

1. Introduction

Currently, the massive growth in Internet traffic has created a surge of bandwidth requirements in todays networks [19], enforcing the deployment of optical wavelength division multiplexing (WDM) technology to guarantee the efficient use of optical bandwidth for extremely high data rates. This trend can be translated into a higher (40/100 Gbps) line rate and dense wavelength division multiplexing (DWDM) transmission systems with 80 to 160 wavelengths per fibre [3]. Hence the advance in optical technologies, from traditional opaque-to-transparent optical network architectures, has become the core of telecommunications and data networking infrastructures for providing enormous capacities in a flexible manner where and when needed in the network. The introduction of coherent techniques such as polarized multiplexed, quadrature phase shift keying (PM-QPSK) enables 100 Gb/s transmission within a 50 GHz channel.

In a transparent network, optical lightpaths are switched completely in the optical domain using network elements called reconfigurable optical add-drop multiplexer (ROADM), therefore reducing the cost considerably as it does not require optical to electrical to optical (OEO) conversions and electronic processing in each node. ROADM is a network element in the transparent optical network that brings flexibility in adding or changing wavelength destination, the process is remotely managed to provide full control and monitoring over the entire high capacity infrastructure [15]. On the contrary, the optical transmission is limited due to accumulation of PLI.

PLI may not be significant in lower-capacity systems, it plays an important role in the new generation systems of transparent networks. Therefore, routing and wavelength assignment (RWA) in the transparent network must consider the signal impairments, as transparency reduces the ability of the client layer to interact with the physical layer, thus leading to limitations on network design, planning, control and management. To mitigate this problem, PLI-aware algorithms are necessary.

1.1. Problem statement& Solution/Objectives

Optical transport networks constitute the basic infrastructure of telecommunications operators and are responsible for transporting most of the traffic generated inside the operator networks. The design of these networks faces many challenges. The traffic is continuously growing, but as the revenues do not follow the same trend it is necessary to devise techniques that permit to reduce the cost per bit transported. these techniques involve using optical channel with a very high capacity ($\geq$100 Gbps) and to resorting on optimization methods to keep the traffic in optical domain if possible, to minimize the utilization of the expensive interfaces required for optical to electrical conversions. However, the optical networks behave as an analogue network and, as consequence; the PLI impact the network operation and must be accounted for in network design. On the other hand, optical transport networks, due to the huge amount of traffic transported, must have a high degree of survivability in the presence of failures, which requires the use of appropriate protection or restoration techniques.

The objective of this thesis is to develop optimization strategies for survivable optical transport networks directed to minimize the network cost considering the PLI. This project is devoted to design survival optical networks, taking into consideration various impairments, due to amplifier cascades and nonlinear effect. Therefore, it is vital to know the penalty due to impairments in the overall system design and developing a network simulator for assessing the performance of the proposed algorithms for different network topologies and traffic demands is also done.

2. Network Planning Aspects

In this Section, all the fundamental concepts related to this work will be explained briefly.

2.1. Routing and Wavelength (RWA) assignment

Routing is the process of finding out lightpaths between the source-destination pair and wavelength Assignment (WA) is reserving a wavelength to that path [15]. This work assumes that there are no wavelength conversions, and the optical connections are static, thus the lightpath must be assigned the same wavelength and lightpaths traversing the same links must be assigned distinct wavelength. These two constraints are called **wavelength continuity** and **distinct wavelength** respectively.

To reduce the computation time considerably [18], there are five sub-problems for RWA problems as follows: **topology sub-problem** to determine the logical topology (mesh), to map on the physical topology, **lightpath routing sub-problem** to route the lightpaths over the physical topology using Dijkstra shortest path routing algorithm, **Traffic routing Sub-problem** for routing the different traffic units between the source and destination edge-nodes over the logical topology used, **lightpath sorting sub-problem** to order the lightpaths (sorting) based on the length of the lightpath in ascending, descending and random manner, and **wavelength assignment (WA) sub-problem** to assign wavelengths to each lightpaths in the logical topology per various wavelength assignment algorithm with a goal to minimize the number of wavelength used in total.

First Fit WA algorithm: All the available wavelengths are indexed. The algorithm goes through the sorted list of lightpaths [6] obtained from the routing sub-problem, and a wavelength with the lowest index is selected from the available wavelengths and assigned to it.

Most-used WA algorithm: In this algorithm, there is a variable to keep count of all the wavelength assigned and their frequency. The wavelength that is assigned to most links is given the highest priority and assigned to the new path if the two constrains of WA are fulfilled, if the constrains are not met then the second-most assigned wavelength will be assigned (only if it fulfils the constraints), and so on.

Random WA algorithm: The total number of wavelengths used in First Fit or Most Used is taken to estimate the available wavelength. Amongst the available wavelength, one wavelength is selected randomly and assigned to the sorted lightpaths. If the total number of wavelength estimated from First Fit and Most Used is not enough, then one wavelength is added to the available wavelength space and the algorithm continues.

Adapted Random WA algorithm: This is a heuristic WA algorithm adapted to get the benefits of both the First Fit and random WA algorithm combined. The wavelength is indexed like in the First Fit algorithm except instead of assigning the lowest indexed wavelength to the lightpath, it chooses randomly one wavelength, which fulfils the two wavelength constraints, from the sets of wavelengths that have already been assigned.

The RWA for networks with protection, follows the same sub-problems. For the dedicated protection, the same wavelength assigned to working path is replicated and assigned to the backup path, subjected to the two wavelength assignment constraints. If one wavelength is assigned to the primary path, then it is replicated for the backup path. The link through which the backup path passes, must also follow the two wavelength constraints of WA. Thus, the program must check these constraints, with its primary path and its backup path and the previous backup path in the same link so that all the wavelengths assigned in the link are distinct wavelengths.

2.2. Load Balancing

While using the shortest path routing algorithm, there are some probabilities that the load distribution is not balanced, meaning some links are utilized more than others. In the shortest path routing, congestion occurs in the most loaded link, and least loaded link are under-utilized. Therefore, it is important to apply load balancing methodology after the shortest path routing is applied to the network, for optimizing the resource utilization to avoid overloading a single link. Load balancing improves the load congestion by mapping part of the traffic, from the most loaded links to the least loaded links. In this work, two load balancing methodologies have been implemented and analyzed. The network is defined as a logical mesh topology, each link with one OTU-4 unit. The Dijkstra shortest path algorithm is applied first, then balancing is done manually by selecting routes from the most loaded link, and reroute it to another alternative shortest path.

The Load Balancing Algorithm 1 [10] uses the second shortest path (Yens k = 2) and the third shortest path (Yens k = 3) balancing schemes for rerouting paths passing through the maximum load link. Suurballe edge-disjoint routing is added to the algorithm to see if it provides better results compared the rerouting schemes the algorithm suggests.

Load Balancing Algorithm 2 [8] reroutes paths passing through the maximum loaded link until the last 10 reroutes do not decrease the most loaded link. It uses edge and node disjoint k-shortest path routing algorithm for re-routing the path from maximum loaded link.

2.3. Survivability

Providing resilience against failure is an important requirement for many high-speed networks [19]. A connection is often routed through many nodes in the network, many elements along its path can fail. Protection is the key technique which ensures survivability, providing redundant capacity within the network, and automatically re-routing traffic around the failure. In case the working path is interrupted by unforeseeable failure events,the diferent path protection schemes, that can create a robust and reliable network design, are: shared and dedicated protection. In shared protection, a single protection path is shared by numerous working paths and for dedicated protection, each service path (working path) must have a backup (protection) path. The protection path must be disjoint from the working path. There are two categories of dedicated protection as following [15]: (1+1) protection where a copy of the working signal is sent over the protection path and (1:1) protection where the backup paths become only active when the working path fails.

For this work, 1+1 protection is adopted. Suurballe [20] algorithm was implemented for computing the protection path which is disjoint from the working path. Suurballes algorithm uses Dijkstra shortest path algorithm to find the working path. The output of the algorithm is formed by combining these two paths (working and backup paths).

2.4. Network Elements (ROADMs)

A lightpath added (originates) at a transmitter in the ingress node, dropped (terminates) at an O/E receiver in the egress node, and it is optically bypassed (switched) at the intermediate nodes which is referred as express lightpaths [7]. These processes are implemented by specialized equipment in the network named ROADM. This equipment is a software-based configuration where a network operator can choose whether a wavelength is added, dropped, or bypassed through the node. ROADM has different node degrees (D), a degree is another term for switching directions and is generally associated with a transmission fibre pair.

The wavelength selective switches (WSSs) are the basic element of RODAM which performs actual wavelength switching, monitoring, multiplexing and demultiplexing. The WSS can select any colour to be routed toward the add/drop side of the local node or bypass to the next node [14]. An optical splitter/combiner is a key passive device to split/combine the optical power evenly from the input port into all NF output port. A generic ROADM has two kinds of ports, fibre ports (connection between two ROADMs) and local ports (connection between ROADM and local transmitter/receiver) [13].

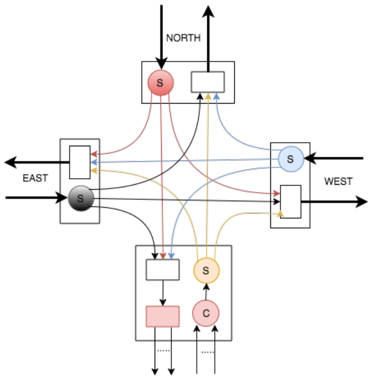


Figure 1: ROADM structure [D=3, Cd=1].

Figure 1 is a three degree ROADM with traffic flowing in three directions (usually referred to as North, West and East). For each direction, one WSS and one splitter is required and for the add/drop module two WSS and Splitter/Combiner combinations is required to complete the ROADM structure. The total number of add/drop module is referred to as contention degree (Cd).

To design a ROADM, each input of splitter(S) should be connected to all the WSS output in other direction and the add/drop module. Combiner (C) outlet connects to the splitter inlets in add section and WSS connects to another WSS in drop section. The Figure 1 illustrates basic ROADM structure.

This structure is typically based on broadcast and select arichitecture. In this work, the new generation if colourless and directionless based ROADM is considered for all the analysis.

Colourless: The colourless ROADM functionality automates the assignment of add/drop wavelengths. Any wavelength can be assigned to any port at the add/drop port [15] rather than having each wavelength assigned to a fixed mux/demux port.

Directionless: Any wavelength can be routed to any direction served by the node with a software instead of physical rewiring, unlike the direction dependent ROADMs.

2.5. ROADM Architecture

Today, ROADMs structure are based on the broadcast-and-select architecture (B&S) and route-and-select architecture (R&S). B&S architecture is constructed by combining the wavelength selective switch (WSS) and the optical splitters (or couplers). In R&S architecture, all the elements are WSS switches. Figures 2.8 (a) & (b) show the two-different architecture and how they are constructed.

In B&S ROADM architecture, on the **add side**, a combiner combines lightpaths originating at the transmitter, in the ingress node, to a common connecting fibre. These combined signals are then distributed to all the outbound nodal degrees through a following splitter. A WSS in a nodal degree combines the signals, from all the other degrees and from the add ports. On the **drop side**, the signals from all the nodal degrees are aggregated on a common WSS, then passed on to a common connecting fibre to another WSS which further splits the signals onto different drop ports [7]. Most transmitters in the optical transport layer are equipped with wavelength tunable lasers and receivers with broadband photo detectors. Figure 2.8 below illustrates a basic colourless, directionless and contentionless ROADM architecture with different combination of nodal degree and contention degree.

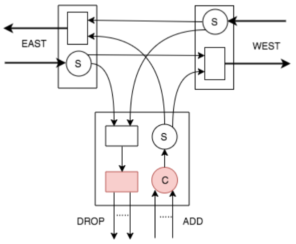


Figure 2: B&S architecture [D=2, Cd=1]

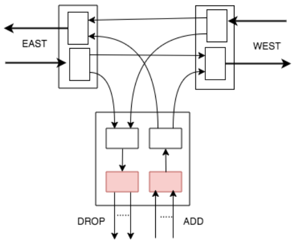


Figure 3: R&S architecture [D=2, Cd=1]

Ⓒ Combiner 1x20 🟥 WSS 1X20 Ⓢ All Splitter 1X8 ☐ WSS 1X9

2.6. Node perspective Evaluation

The analysis of the ROADM node structure is done to study the impact of node degrees on the contention degree. The model assumes that all the connections are bidirectional and requires several input parameters, that are defined below, these are the specifications used in this work. This model is derived from the analysis of Figure 2 & 3.

- Node degree D;
- Contentionless degree Cd;
- Number of Splitter inlets (outlets) for all the splitters (1x8) S ;
- Number of combiner inlets (outlets) for the combiner at add module in Route and Broadcast ROADM architecture (1x9) C_{bs};
- Number of WSS inlets (outlets) in direction section (1x9)P_{wss1} ;
- Number of WSS inlets (outlets) for the add/drop section (1x20)P_{wss2};
- Number of transmitters (T_x) and receivers (R_x) T;

The number of connections (inlets/outlets) used by splitter and WSS (1x9) in the add/drop module denoted as Λ, is directly propertional to the node degree D:

$$\Lambda = D \tag{1}$$

The number of connections (outlets/inlets) used by splitter and WSS (1x9) in the direction section Γ , is given by

$$\Gamma = Cd + D - 1 \tag{2}$$

The number of transmitters (T_x) and receivers (R_x) in the node are given by following equations: For B&S ROADM architecture, it requires a combiner (1x9) and a WSS (1x20), T can be written as:

$$T = (P_{wss2} + C_{bs}) * Cd \tag{3}$$

and for the R&S ROADM architecture, it requires two WSS of (1x20) size, one each for add and drop module. Then:

$$T = (2.P_{wss2}) * Cd \tag{4}$$

3. Impairments Aware Network Planning Strategy

This Section will include all the analysis of lightpath computation with PLI.

3.1. Physical Layer Impairments

As the optical signals traverse through an optical fibre links and propagates through passive and/or active optical components, it makes them susceptible to impairments that affect signal intensity level. PLIs are broadly classified into two categories: linear and non-linear. Impairment compensation depends on what kind of detection techniques is used, because coherent detection with advance digital signal processing (DSP) algorithms, enables electrical (offline) compensation for the impairments due to fibre transmission. This work is an optical network design based on coherent detection considering only linear impairments (Amplified Spontaneous Emission noise) and a simplified non-linear impairment that is not compensated by coherent detection. However, common PLI are discussed below to give a general idea about the different impairments in existence. Performance of the transparent optical transmission is mainly limited by ASE noise accumulation and the generation of nonlinear interference (NLI), due to the Kerr effect in the fibre [16].

Amplifier Spontaneous Noise (ASE): The main source of noise in optical channels is the amplified spontaneous emission noise, produced by OA used as intermediate repeaters and as preamplifiers at the receiver end. OA generate ASE, which is subsequently amplified on the line. ASE is quantified with noise figure (NF), which allows to know how much higher the noise power spectral density, of the amplified output, is compared with the input noise power spectral density times the amplification factor [11]. This effect can be alleviated by increasing the input laser intensity (transmitter power), decreasing the amplifier facet reflectivity, or by tuning the master oscillator so that it is resonant with the amplifier [1]. However, increasing the transmitter power would increase the non-linear effect.

Non-Linear Impairments (NLI): Non-linear effects can be minimized by using lasers with lower transmitter powers by implementing a large effective area (Leff) fibre. Recently, digital signal processing techniques also include nonlinear compensation. However, when the power in optical networks is increased, the signal distortion from nonlinearity also increases. The primary NLI phenomenon limiting the transmission of signals is Kerr nonlinearity [2]. The effect of NLI (Kerr effect), can be approximately modelled as excess additive Gaussian noise that is statistically independent of ASE noise [16].

3.2. Impairments Aware Routing and Wavelenth Assignment

Impairtments aware RWA inspired from [5] [11] with the objective of assigning routes and wavelengths to the traffic demands in order to satisfy impairment constraints while also minimizing the number of wavelengths used. The design procedures are shown in the flowchart Figure 4. It illustrates the flow chart of RWA taking PLI into consideration. Next, the following tasks are carried out for each lightpath to design a network. The parameters for all the components are based on industry standards.

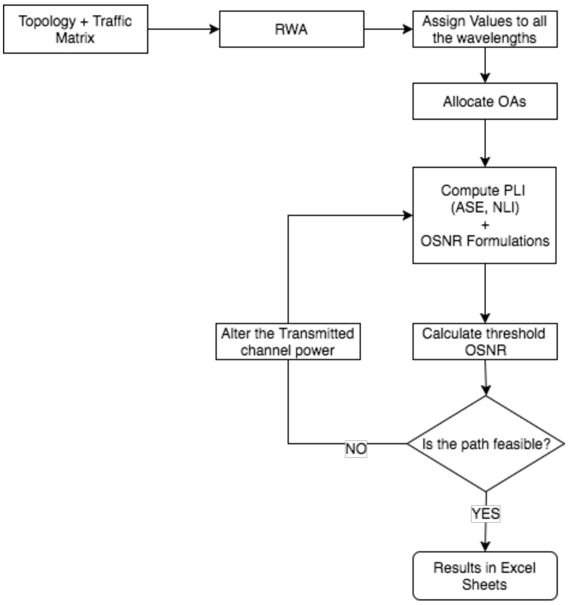


Figure 4: Flow chart of lightpath computation in the presence of PLI

- **Routing and Wavelength Assignment:** Route the lightpaths and assign wavelengths to each lightpaths in the logical topology according to various wavelength assignment algorithm as discussd in Section 2.1.
- **Assign Values to wavelengths:** All the wavelength used are assigned with its own wavelength value. To find the values of wavelengths, firstly find the spacing in the wavelength domain ($\Delta\lambda$), from the following relation [15]:
$$\Delta v \cong \frac{c}{\lambda_0^2}\Delta\lambda \tag{5}$$
where c is the speed of light in the vacuum ($3 \times 10^8 m/s$). Substituting all the values in (5), it would give wavelength spacing equal to 0.4 nm. So obtain all the values of wavelengths with spacing 0.4 nm.
- **Allocate the OAs**: OAs are used as intermediate nodes between the two ROADMs to

boost the signal power and for optical filtering in ROADMs. For a transmission fibre, after every 80 km (for todays transparent optical network) of fibre span, an OA is placed to compensate the fibre losses. There is pre-amplifier before each ROADM to compensate the losses of the previous span of the fibre and post-amplifier at the end of the ROADM to compensate the pass-through losses light path. Inside the ROADM, there are two OAs placed in add and drop section to compensate the losses from the splitter/combiners and WSSs respectively.

- **OSNR Formulations**: For the development of lightpath computation, ASE noise accumulation and nonlinear effect are considered. The nodes in the physical layer of transparent optical networks, are cascaded ROADMs and the links are optical fibres. OAs are placed periodically at repeated intervals to boost the signal power. OA are placed on the optical fibre to provide gains to the signals and to ensure that the optical signal-to-noise ratio (OSNR) is greater than a threshold that permits detecting and decoding signals at the end receiver [15]. The OA also adds its own component of ASE noise and degrades OSNR further. Hence, it is vital to plan a method to calculate the OSNR (output) at the end of an N stage-amplified system. The OSNR is an important factor associated with an optical signal to check the feasibility of the wavelength. Therefore, optical networks are designed to adhere to OSNR measurements. OSNR is essential because it advocates a degree of impairment when the optical signal is carried by an optical transmission system that includes OA.

  Coherent detection achieves higher spectral efficiency and PLI are compensated mostly in electrical domain [11]. Therefore, only two primary factors that degrade signals in an optical network that are taken into consideration for this work: noise (ASE) and relatively small nonlinearity (caused by Kerr effect). In a coherently-detected PM-QPSK system, the data traffic is mapped into I and Q signals, inphase and quadrature, respectively in two orthogonal states of polarization [11], hence the power of ASE noise (P_{ase}) in (6) is divided by 2. OSNR is computed as (7).

  $$P_{ase} = \frac{(fn(i).hv.g(i).Bn)}{2} \tag{6}$$

  $$OSNR = \frac{P_{Tx,ch}}{P_{ase}} \tag{7}$$

  where, h is the plank's constant (6.6260×10^{-34}), v is the corresponding optical frequency for the practical wavelength values used, $P_{Tx,ch}$ is the transmitted channel power, Bn is the practical bandwidth for the channel corresponding to the bitrate of a channel ($100 GBps$) and $fn(i)$ is the noise figure (NF in dBs) of the amplifiers which directly depends on the corresponding amplifier gain values $g(i)$. N of corresponding OAs gain are obtained from the interpolation of NF values at three different OA gains (NF = 11.5 dB at 12 dB gain, NF = 6.5 dB at 20 dB gain and NF = 5.7 dB at 12 dB gain of OAs respectively [22]).

  For the analysis in this work, all the links are bidirectional links for the simulations and modelling. The lightpath traverses several OAs and ROADMs along its path. The schematic in Figure 5 shows cascaded ROADMs in the optical network for path computation with PLI.

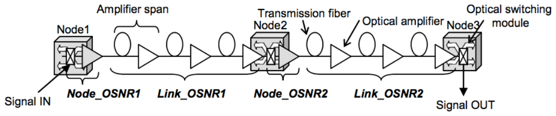


Figure 5: Components utilized for path computation in OTN

  OSNR for a point to point link is given by summing all the reciprocal of OSNR of links and nodes the lightpath passes through and the analysis is derived from [23]. Figure 5 also illustrates the link_OSNR and node_OSNR.

  Node_OSNR is the total OSNR of all the nodes that the lightpath passes through, so it is decomposed into $OSNR_{add}$, $OSNR_{drop}$ and $OSNR_{express}$ (OSNR at add, pass-through and drop ROADMs respectively) for simplifications. Therefore, the Node_OSNR having L traversed ROADMs is as follows,

  $$\frac{1}{Node\_OSNR} = \frac{1}{OSNR_{add}} + \frac{L}{OSNR_{express}} + \frac{1}{OSNR_{drop}} \tag{8}$$

  The link (optical fibre) consists of M numbers of amplifier spans and a pre-amplifier to compensate the losses from the previous span of the fibres. The optical link is limited by both ASE noise accumulation and the generation of nonlinear interference (NLI) [16] which is due to the Kerr effect in the fibre.

  Link_OSNR considering the power of ASE noise alone. For a link consisting of M numbers of amplifier spans for coherent detection, the $amplifier_span_OSNR$is:

$$amplifier\_span\_OSNR_i = \frac{P_{Tx,ch}}{P_{ase}} \tag{9}$$

$$Link\_OSNR = 1/\left(\sum_{i=1}^{M} \frac{1}{amplifier\_span\_OSNR_i}\right) \tag{10}$$

where $amplifier\_span\_OSNR_i$ is the OSNR of $ith4$ amplifier span.

Now considering nonlinear interference (NLI), for coherent detection, the performance evaluation can be done using the Gaussian noise (GN) approach. The GN model in dispersion-uncompensated transmission, assumes that the (NLI) caused by Kerr effect is relatively small. NLI can be modelled as additive GN which is statistically independent of signal and ASE noise [16]. The power of nonlinear impairment is given by (11):

$$P_{NLI} = (2/3)^3 N_s \gamma^2 L_{eff} P_{Tx,ch} \times \\ \times \frac{\log(\pi^2|\beta_2|L_{eff} N_{ch}^2 R_s^2)}{\pi|\beta_2|R_s^3} \tag{11}$$

where, $P_{Tx,ch}$ is the transmitted channel power, N_s is the number of spans in a link, γ is the fibre nonlinearity coefficient in [1/W/km], β_2 is fibre dispersion in [ps^2/km], RS is the baud rate of a channel in [GBaud], N_ch is the number of channels (wavelength) traversing in each link, and L_eff is the fibre effective lengt in [km].

$Link\_OSNR$ from (10) changes to (12) when the OSNR is calculated in the presence of both linear and nonlinear fibre transmission effect [16].

$$Link\_OSNR = \frac{P_{Tx,ch}}{P_{ase} + P_{NLI}} \tag{12}$$

where, P_{NLI} is the NLI noise power.
In general, a lightpath traverses several OAs and ROADMs along its path [4]. In this case, the end-to-end OSNR (Total_OSNR) of having L ROADMs and (L-1) links for a lightpath is be given by,

$$\frac{1}{Total\_OSNR} = \frac{1}{OSNR_{add}} + \frac{1}{OSNR_{drop}} + \\ + \sum_{i=1}^{L-1} \frac{1}{Link\_OSNR_i} + \frac{L}{OSNR_{express}} \tag{13}$$

where, $OSNR_{add}$, $OSNR_{drop}$ and $OSNR_{express}$ are the OSNR at add, drop and pass-throughROADMs respectively, and M is the number of optical fibre spans.

- **Feasibility**: To check the feasibility of all the wavelengths, threshold OSNR, $OSNR_{Required}$ is calculated as shown in(14). $OSNR_{Total}$ obtained should be greater than or equal to the $OSNR_{Required}$ for a path to be feasible.

  $$OSNR_{Required} = OSNR_{ideal} + M_s + Penalty \tag{14}$$

  where,$OSNR_{ideal}$= 12.3 dB, 17 dB and 20.2 dB for PM-QPSK (100 Gbps), PM-QPSK (150 Gbps) and PM-QPSK (200 Gbps) [12] modulation scheme respectively, Ms is the system margin given by (15), and the penalty is due to optical filters in WSSs. System Margin results from several sources, the impact of aging, power ripple along the transmission bandwidth, and polarization-dependent loss, which is taken into account by considering a fixed system margin of 0.05 dB every time an OA or ROADM is traversed by a lightpath [4].

  $$M_s = 0.05 \times (N_{OA} + N_{ROADM}) \tag{15}$$

  where, N_{OA} is number of OA used and N_{ROADM} number of ROADMs in which the lightpath transverses. ROADM performs optical filtering to transmitted signal, leading to signal degradation. In [17], the OSNR penalty due to optical filtering in WSSs for 28 GBd is presented.

To compute OSNR of every ROADM, that the lightpath transverses through, it is important to know the architecture of ROADM and how the components are equipped inside it. The illustration in Figure 4.3 is an example of B&S ROADM architecture and the same formulation is done to R&S architecture. The OAs are used to compensate the losses due to passive components (splitters, combiner and WSS) inside a ROADM, but it also generates ASE which impairs the lightpath.

From [9] it can be concluded that the insertion losses of a (1x9) WSS is about 3 to 4 dB, and for (1x20) is about 4.5 to 5.5 dB. It is also referred in [21] that the values of specifications (data sheets) are typically 1-2 dB higher, which leads the WSS(1x9) and WSS (1x20) to have 6 and 7.5 dBs of losses respectively. Hence, these values for insertion losses are used for the analysis.

4. Simulation Experiments

All the simulations and tests were executed by creating function in MATLAB2015b software. A simple connected graph $G = (V, E)$ represents the network topology of NSFNET as shown in Figure 7, where V denotes the set of nodes (ROADMs) and E denotes the set of single-fiber links. Then a netCostMatrix is derived from the link cost (network costs in Kilometres) from the physical topology of

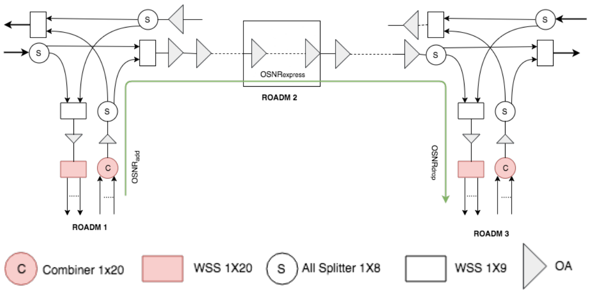


Figure 6: Lightpath formulation between the two nodes

all the networks to use as an input for all the simulations carried out. The traffic matrix is constituted by nonnegative integers known a-prior, this work only considers static networks i.e., a mesh logical topology with 1 unit of traffic (OTU-4) between all the nodes (1 unit of traffic = 100 Gbps) is used for this work generally. It will be mentioned before the results if different traffic units are used.

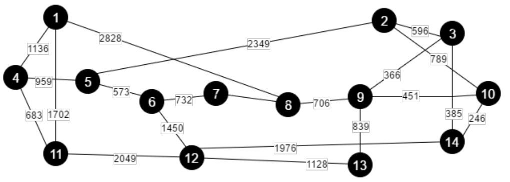
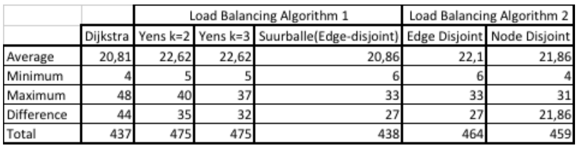


Figure 7: Physical topology for NSFNET network (cost of network in [km])

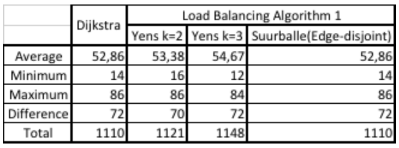
Routing and Load balancing:



		Load Balancing Algorithm 1			Load Balancing Algorithm 2	
	Dijkstra	Yens k=2	Yens k=3	Suurballe(Edge-disjoint)	Edge Disjoint	Node Disjoint
Average	20,81	22,62	22,62	20,86	22,1	21,86
Minimum	4	5	5	6	6	4
Maximum	48	40	37	33	33	31
Difference	44	35	32	27	27	21,86
Total	437	475	475	438	464	459

Figure 8: Load Distribution in networks before and after Load Balacing

Clearly load balancing algorithm II is better than load balancing algorithm I in general because the algorithm II has a better probability of balancing the network, this is due to the program finding the best reroutes in order to reduce the maximum link load in the network, until the last 10 reroutes do not reduce the maximum link load. It uses edge and node disjoint for re-routing the paths from the maximum loaded link which reduces the chance of passing through the congested link again. It is also observable from Figure 8.

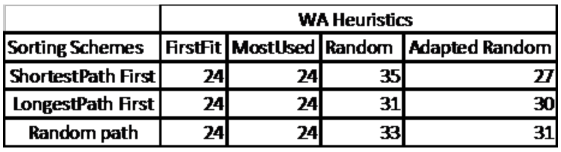


	Dijkstra	Load Balancing Algorithm 1		
		Yens k=2	Yens k=3	Suurballe(Edge-disjoint)
Average	52,86	53,38	54,67	52,86
Minimum	14	16	12	14
Maximum	86	86	84	86
Difference	72	70	72	72
Total	1110	1121	1148	1110

Figure 9: Load Balancing in network with the protection

Figure 9 shows the load distributions after balancing, when the protection path is added. Only the results of load balancing algorithm 1 with its three different rerouting methodologies are represented here, as there was almost no improvement in balancing using both the algorithms.There is almost no alteration in load distribution in all the three networks using the different methodologies of rerouting after the protection path is added, resulting an unbalanced network. In the dedicated protection scenario, when the primary (working) path or backup path passing through the maximum loaded link, is rerouted, the corresponding new disjoint primary or backup path should be computed simultaneously. However, this new path found has higher probabilities of containing the maximum loaded link in it. Therefore, preventing the load balancing in the network.

Routing and Wavelength Assignment: Traffic demand is a mesh logical topology with 1 unit of traffic (OTU-4) between all the nodes. Figure 10 shows the total number of wavelengths used by each WA heuristics using the three different sorting schemes. The total number of wavelengths used for the same network greatly depends on the WA heuristic algorithm chosen as well as the sorting schemes of the lightpaths. The first fit and mostused WA uses slightly less total number of wavelengths than the other three WA heuristic algorithms.



	WA Heuristics			
Sorting Schemes	FirstFit	MostUsed	Random	Adapted Random
ShortestPath First	24	24	35	27
LongestPath First	24	24	31	30
Random path	24	24	33	31

Figure 10:

Impairments aware Routing and Wavelength Assignment: The experiments were performed assuming a NSFNET network topology with link cost as shown in Figure 7, with its nodes assumed to be ROADM. Each link was assumed to consist exclusively of SSMF fibers with dispersion parameter D=17 ps/nm/km and attenuation parameter α=0.22 nepper/km. The launch power ($P_{Tx,ch}$) was set from -10 dBm to 10 dBm to be able to have a huge data to improve the result analysis. Since, there was no or very small changes (if there was any) in outcome using different RWA heuristics and path sorting schemes, the results from only one WA heuristic (First Fit) are presented here for the two different ROADM architecture (Broadcast & select and Route & select) to avoid the redundant results. The two architecture have different $OSNR_{Required}$ due to its building components. These results are for the worst lightpath in NSFNET. The worst lightpath in NSFNET network was 1−¿4−¿5−¿2 with total distance of 4444 [km]. The results obtained in Figure 10 and Figure 11 are for this worst lightpath. The $OSN_{Required}$ for the worst lightpath in the network is 15,575 [dB] for B&S architecture and 16,575 [dB] for R&S architecture.Total_OSNR was obtained for 20 different $P_{Tx,ch}$.

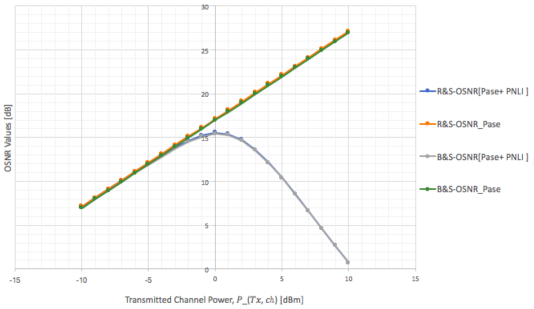


Figure 11: Total_OSNR as a function $P_{Tx,ch}$ for both the architectures for NSFNET network

In B&S architecture (for ASE accumulation only), the minimum $P_{Tx,ch}$ required for the lightpath to be feasible is 2 dBm and more, whereas for R&S architecture it is from 3dBm and more. When both ASE and nonlinear is taken into account, the lightpath is not feasible for any of the $P_{Tx,ch}$ for both the architecture. As the link cost (distance between the two nodes) are huge, the path is not feasible for all the $P_{Tx,ch}$, when nonlinear effect is considered. From Figure 11, It can be witnessed that the OSNR values for the both architectures are almost the same when its only from ASE noise and when the nonlinear effect is considered for all the $P_{Tx,ch}$ values.

5. Conclusions

In the transparent optical networks, PLIs suffered by optical transmission medium and ROADMs accumulate along an optical path. To determine the feasibility or transmission quality of the lightpaths, the received signal quality should be within certain threshold values for a receiver to detect the optical signal correctly. In this work OSNR was used as a feasibility metric. Hence, several PLIs and their effects were investigated first, then studied their effect on the optical feasibility (OSNR), and a mitigation technique was adopted to set up and manage the lightpaths.

The use of the shortest path routing algorithm leads to an unbalanced network, hence load balancing must be applied to distribute the loads as uniformly as possible throughout the links. Nonetheless the two balancing algorithms did not improve balancing in the networks when protection paths were added. RWA was used to determine the best possible routes and reduce the use of available wavelength. The adapted random WA algorithm used lesser number of wavelengths in total for COST239 and UBN networks, and First Fit and Most Used WA algorithms used minimum number of wavelengths in NSFNET network. The contention degree of a ROADM depends significantly on the RWA heuristic and path sorting algorithm used.

For an analytical approach considering the modelling the PLIs for computing and establishing an optically feasible lightpaths to meet the required received signal quality (OSNR), the lightpath feasibility depends on ROADM architecture, link cost (distance) between the two ROADMs when considering nonlinear effect, and the transmitted channel power chosen. If the lightpath is not feasible, $P_{Tx,ch}$ is altered. Non-linear effects can be minimized by using lasers with lower $P_{Tx,ch}$ by implementing a large effective and ASE by increasing $P_{Tx,ch}$.

Hence it is vital to choose a proper $P_{Tx,ch}$. Different RWA heuristics and path sorting schemes did not alter signal quality notably, unlike the path computation without the PLIs.

6. Future work

The following list provides several area of future research for this work:

Implementation of OSNR formulation framework to higher spectral efficiencies modulation formats.

An approach considering the survivability (protection) in PLI constrained optical networks.

Explore and implement more feasibility mitigation techniques to establish an optically feasible lightpaths (such as adding transponder, regenerator, traffic grooming, etc.) and to increase the optical reach of lightpaths.

Lightpath monitoring with more feasibility metric (e.g. BER, Q-factor, etc.) to obtain concreate lightpath feasibility conclusion.

Wavelength assignment in the presence of wavelength converters and dynamic traffic scenarios.

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