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An Optimised Resource Provisioning Algorithm for Transparent Optical Core Networks

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Comparing transparent optical core networks (TOCNs) to their opaque and translucent counterparts, TOC- Ns are usually thought to be more energy efficient. Because of this, they are also considered a workable solution for transport networks that need to provide extremely high bandwidth to support a wide range of services and applications. These wavelength-routed networks are spectrally inefficient due to the ensuing diverse nature of current global traffic. But the spectral efficiency and optical reach of these networks have significantly increased thanks to developments in DSP, modu- lation, and transmission impairment mitigation techniques.
Thus, an orthogonal frequency division multiplexing (OFDM) based TOCN with flexible spectral resource provisioning is reviewed in this paper. We discuss how to strike a balance between spectrum efficiency and resource provisioning at the wavelength routing level. We also propose and evaluate a Q- factor based technique that takes into account different limita- tions in the physical layer. both simulation and analytical methods. Overall, the suggested architecture for the transport network is relatively more efficient in terms of both energy and spectrum utilization.

Keywords: Transparent Optical core networks, blocking probability, physical impairments, spectral efficiency, success ratio.

1. Introduction

By performing optical switching TOCNs allow an opti- cal signal to traverse the network without requiring any conversion to electronic domain forms. By maintaining the network connection in the optical domain from source to destination, these networks hope to do away with the inter- mediate electrical circuitry that is typically more costly and less scalable than optics.

Since these networks lack optical-to-electrical-to-optical (O-E-O) conversions, their current geographic reach is lim- ited [1]. Transparent TOCNs are to be highly lucrative because they are relatively inexpensive and have minimal carbon footprints, particularly given the absence of O-E-O convert- ers. Although they have a number of noteworthy benefits, they also come with certain operational and technical limi- tations. Limitations on passive switching and wavelength continuity constraints that result in high levels of connec- tion blockings are some of the main issues they present. However, some of the challenges that were present in their previous system versions were recently solved by re- lated latest advances in optical technologies in particular amplification. The attainment of an optical reach exceeding 30,000 meters has been achieved by the use of Raman am- plifiers at ingress nodes as opposed to their Erbium doped fiber amplifier (EDFA) equivalents. Current research is focusing on expanding the reach and minimizing energy consumption. The utilization of photonic integrated circuits (PICs) has improved the feasibility of these networks by integrating various WDM components on a single chip. Furthermore, the replacement of fixed transponders with tunable counterparts has reduced capital costs, and wave- band-based switching has led to cost and energy savings. TOCNs provide transparency to protocols, speeds, and sig- nal formats, making them a promising solution for accom- modating increasing bandwidth demands. However, physi- cal-layer impairments (PLIs) can impact network perform- ance due to the absence of signal refreshment functional- ities at nodes. Flexible bandwidth networks can enhance spectral usage efficiencies by dynamically controlling spec- tral efficiency based on PLIs levels to ensure consistent quality of service. To improve routing decision-making, it's crucial to understand and monitor PLIs levels and incorpo- rate network mechanisms to furnish them to the control plane. This constitutes the fundamental PLIs aware routing and wavelength assignment (RWA) problem in Transparent TOCNs. The main objective is to maximize the number of simultaneous end-to-end lightpath connections with mini- mal resource provisioning. To address this, a comprehen- sive resource provisioning framework for such networks is proposed, with a focus on wavelength routing level versus energy efficiency. The paper is structured as follows: a re- view of a generic TOCN architecture, followed by PLIs aware RWA, a discussion of a model and resources alloca- tion framework considering PLIs and energy efficiency, and an evaluation of the efficacy of a Q-factor-based tool and analysis of overall network energy efficiencies.core net- work archtecture. Both video and Internet based applications and services have lead to an exponential growth in global traffic. This has lead to a demand for greater transmission as well as switching capacity demands. At transmission level, dense wavelength division multiplexing (DWDM) has to an ex- tent addressed the solution. However adaptable switching and routing approaches still need to be integrated with DWDM in order to design a high capacity spectral and energy efficient Transparent TOCN. Because the traffic volumes keep on relentlessly surging, a corresponding con- stant upgrading of capacity in existing such networks is also necessitated. In this regard, integrating novel features in to the optical layer will ensure more flexibilities at both over- all network and channel levels .

According to various current estimates, global traffic growth trends on a year by year basis are ten times rapid than corresponding system bandwidth increases. As a result, there is thus a need to introduce novel scaling inter- face rates as well as system bandwidth to match the traffic volumes. This requires a break through in this regard, on a less similar scale to the inception of dense wavelength mul- tiplexing technology.

It is further estimated that the Optical Wavelength Service (OWS) market which primarily offers users dedicated broadband lines, will grow by 10% or more from 2020 to 2025.

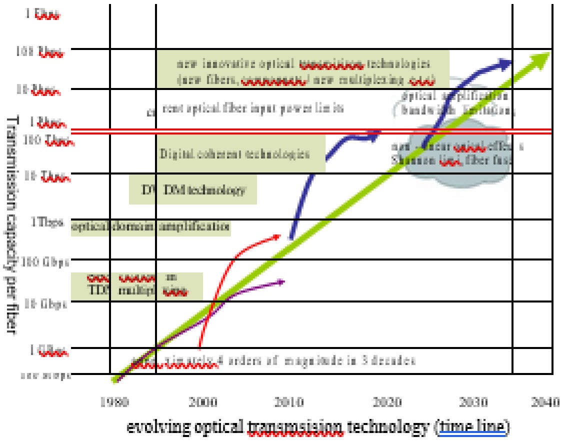

Fig.1: Evolving in Optical transmission speeds

The last thirty years have seen significant advancements in optical transmission technologies, largely due to techno- logical innovations such as time division multiple access (TDMA), space division multiplexing (SDM), optical am- plification and filtering technologies, DWDM, and digital coherent technology. While research has shown the poten- tial for achieving speeds of up to 1 Pbps, the current optical medium and multiplexing technologies are approaching their physical limits. However, the ongoing rise of indus- trial automation and the Internet of Things (IoT) are ex- pected to significantly increase data traffic, creating a greater demand for high-capacity optical transport networks for both large corporations and Small and Medium-sized Enterprises (SMEs). It is anticipated that by 2023, the aver- age GSM smartphone will generate over 16 GB of data per month, further emphasizing the need for enhanced optical transport networks.

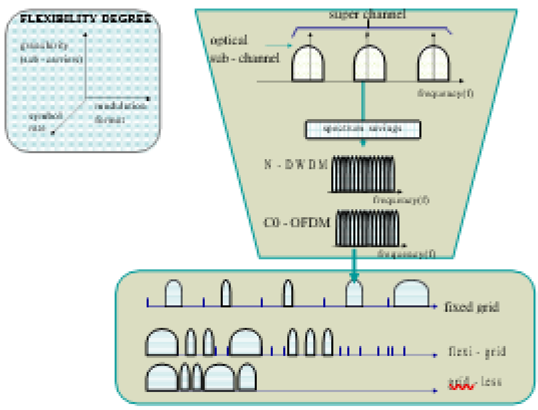

Fig. 2: A Flexible TOCN Configuration.

The continuous development of the Internet of Things (IoT) and device-to-device (D2D) communications is expected to result in a significant increase in data production. It is projected that the global number of installed IoT devices and objects will exceed 75.44 billion by 2025.

The anticipated widespread adoption of 5G mobile technol- ogy is likely to lead to a rise in global subscriptions to 2 billion by 2025, which will further drive the utilization of IoT in our daily lives.

Market growth may be somewhat constrained by a surge in the demand for virtual connectivity and the limited avail- ability of scalable optical interfaces. The escalating global traffic and scalable capacity requirements have created a need for optical interfaces in the TOCN to scale from the current 10 Gb/s, 40 Gb/s, and 100 Gb/s to 2-3Tb/s by 2025. A proposed approach involves creating a "super-channel" through the aggregation of densely packed sub-channels. This will enable a flexible optical networking system to optimize the utilization of available resources within the Optical Transport Network, dynamically adjusting re- sources such as assigned wavelength channels, path con- figurations, transmission formats, and data rates based on varying traffic conditions.

There are ongoing advancements in designing TOCNs that dynamically allocate resources based on actual demand, combining technologies such as OFDM, Nyquist WDM (N- WDM), and coherent transmission. It is envisioned that these developments will lead to the realization of a fully flexible TOCN, capable of dynamically adapting to the re- source needs of each live end-to-end lightpath connection, thereby efficiently utilizing key network resources such as available spectrum and wavelengths.

Additionally, to facilitate standardized implementation, ITU's recommendation G.709 has defined an Optical Transport Network (OTCN) standard, which integrates leg- acy features such as SONET/SDH to WDM equipment. This establishes a seamless, transparent, hierarchical net- work designed to accommodate both WDM and TDM ele- ments and devices, defining switching, transport functions, survivability, routing, multiplexing, management, and su- pervision.

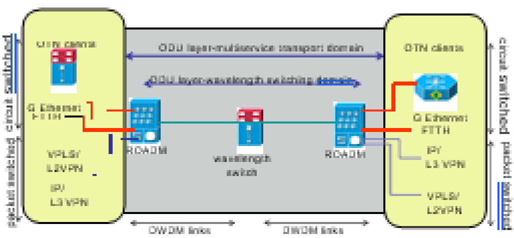

Fig. 3: Optical Transport Network Model

The G.709 standard outlines a standard frame format com- prising six distinct layers. These layers include the Optical Channel Payload Unit (OPU) for identifying and describing data type, the Optical Data Unit (ODU) for optical path- level monitoring and protection switching, and the Optical Transport Unit (OTU) for performance monitoring and er- ror correction. The Optical Channel (OCh) represents an end-to-end optical path, while the Optical Multiplex Section (OMS) is for fixed DWDM deployed between Optical Add Drop Multiplexers (OADMs). The Optical Transport Sec- tion (OTS) deals with fixed wavelength DWDM between relays. Integrating SDN into Transparent OTNs would greatly enhance flexibility and adaptability in routing and wavelength assignment (RWA) scenarios, enabling end users to independently innovate new overlay networks and services without requiring infrastructural changes.

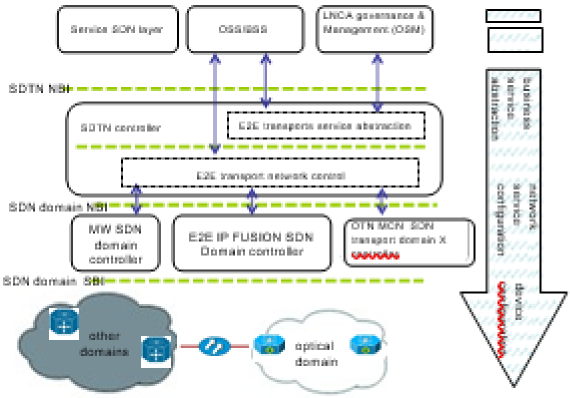

Fig. 4: SDN architecture

The main functions of the flexible TOCN include dynami- cally assigning wavelengths and other bandwidth resources for end-to-end lightpath connections. This allows for flexi- ble support for mixed line rates, enabling end users to re- quest specific data rates. This approach increases spectral efficiencies for coarser wavelength granularity and en- hances wavelength utilization for sub-wavelength granular- ity. The flexibility of the channels is achieved using vari- able rate transponders (VR-TPND), and a software-based automated control plane ensures that network resources are appropriately sized for traffic distribution, optimizing rout- ing and resource assignments. [9]

2. Physical Impairments Aware RWA

Transparent optical transport networks are often seen as a cost-effective solution for high-speed transmission and switching networks, particularly for bandwidth-intensive applications. These networks are energy-efficient due to the lack of repeaters, but they still suffer from signal degrada- tion caused by physical layer impairments. The absence of repeaters can result in compromised signal quality and overall poor quality of service. Introducing repeaters would help refresh the signals when necessary. Physical impair- ments also limit the number of simultaneous end-to-end lightpath connections, requiring approaches to address these issues during network establishment. One such approach, impairment-aware routing and wavelength assignment (IA- RWA), aims to avoid paths and links susceptible to high levels of signal impairments. Common linear impairments in optical networks include polarization mode dispersion, chromatic dispersion, fiber attenuation, polarization- dependent losses, crosstalk, filter concatenation, amplified spontaneous emission, and component insertion losses. Ad- dressing the IA-RWA problem is crucial to ensuring consis- tent and acceptable quality of transmission in transparent optical transport networks. Various literature explores dif- ferent approaches aimed at addressing transmission im- pairments in network design and operation, [10], [11], [12].

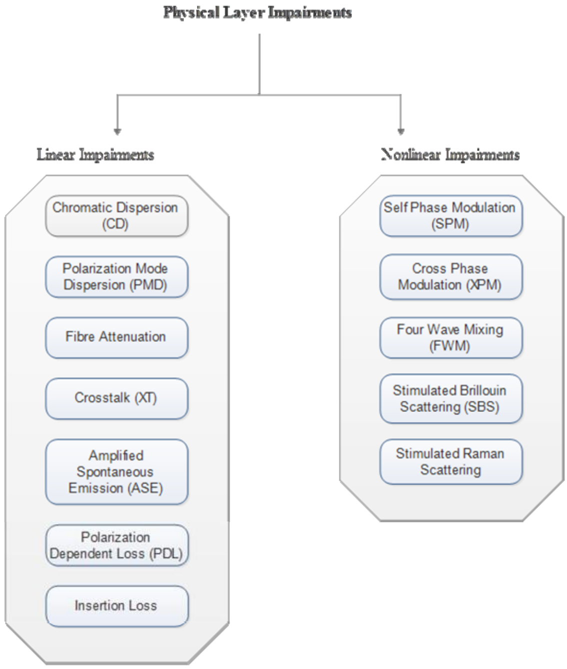

Fig. 5: Physical impairments.

The typical steps involved in addressing physical im- pairments include assessing potential paths and wavelengths using existing RWA algorithms and confirming signal qual- ity by accounting for the effects of physical layer impair- ments. PLIs are considered during RWA processes. Addi- tionally, the signal quality of selected lightpaths is verified before traffic is dispatched. One study introduces a shortest- path RWA algorithm aiming to identify primary and protec- tion links that adhere to the end-to-end wavelength- continuity constraint. It computes the Q-factor of candidate paths and selects the one with the highest Q-factor to establish a new connection. Another study presents k-SP based IA-RWA algorithms that address common impairments such as ASE, GVD, and PMD by enforcing Q-factor penalties and utilizing them to compute edge weights. Comparison reveals that IA-RWA algorithms and online routing algo- rithms are computationally intensive, whereas online IA- RWA algorithms demonstrate lower blocking probabilities. However, both algorithm categories do not account for all key impairments and may not be suitable for high-capacity networks operating at speeds exceeding 100 Gb/s. Another approach explores ILP formulation and heuristic methods for computing candidate routes using link costs derived from ASE and PMD effects. Authors in another study consider XT in RWA decision-making and propose a dynamic com- putation-based adaptive routing algorithm to calculate Q- factor values from active network devices. In a different study, algorithms are proposed to compute the k-SP using Q penalties as path costs, with the decision to establish a con- nection request based on a comparison between a preset IA threshold and computed Q-factor. Finally, an algorithm in a separate study selects a route by initially assessing signal degradation due to PLIs at each active network node.

3. Network Model and Proposed Resource Provisoning Algorithm

In this section, we present a comprehensive resource allocation framework that accounts for the impact of PLIs and energy efficiency in operating a flexible Transparent OTN, as depicted in Figure 6. The network is assumed to be entirely optical and does not include any WCs at intermediate nodes or line amplifiers. The network's components consist of VTR-TPNDs, variable rate, colorless and directionless reconfigurable optical add drop multiplexers (VR, CL & DL ROADMs), and transponder aggregators (TPND aggregators). The combination of TPND Aggregators and VR, CL & DL ROADMs offers complete colorless functionality, where each physical add/drop port is not wavelength-specific, and directionless functionality, allowing any transponder to connect to any degree [20]

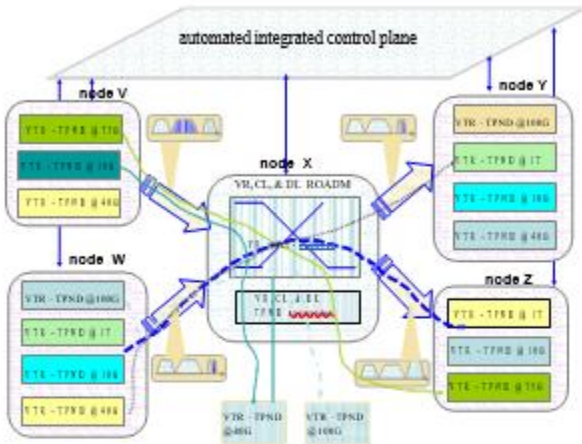

Fig. 6: Overall flexible TOCN architecture

Each complete connection comprises multiple sections. Boosting of signal strength is only possible at the start and end of each segment to counter any signal loss that occurs within each segment. Additionally, we consider that the connections are susceptible to extra noise, and due to the absence of signal regenerators, the impact of signal impairments must be considered. These impairments reduce the quality of the optical signal, which in turn affects the quality of transmission and error rates on the affected routes. The infrastructure of this network deals with routing that is mindful of such impairments, while also ensuring efficient use of energy in the network operations..

A) Routing and wavelength assigning

Three distinct methods for fitting wavelengths, including Random, First Fit, and Round Robin, are being evaluated for selecting candidate paths. These methods will be incorpo- rated into a fitness function to assess wavelength availabil- ity. factor. Wx . We first define the following:

- $I^{lp}_{i,j}$ -an indicator whether link (i,j) belongs to a given lightpath.
- $I^{lp}_{i,j,k}$ -is an indicator that the lightpath connection uses wavelength w on link (i,j).
- $I^{l,p(x,y)}_{i,j,w}$ -lightpath wavelength occupancy indicator, which is set to one if the lightpath connection uses wave- length w on link (i,j) between nodes x and y.
- $l^{(x,y)}$ -is the physical link.

Because each end-to-end lightpath connection is assigned its own unique wavelength, we therefore can define the key wavelength constraints pertaining to general RWA as fol- lows:

$$I^{lp}_{i,j} = \sum_{w=0}^{W-1} I^{lp}_{i,j,w} \quad \forall (i,j) \tag{1}$$

Since it is obligatory that wavelength continuity must be maintained end-to end , we thus have;

$$I^{lp(x,y)}_{i,j,w} \le I^{lp}_{i,j,w} \quad \forall (i,j),\ (x,y),\ w \tag{2}$$

Two or more lightpath connections may share the same the same fibre (link), provided each is assigned is own unique wavelength hence we write;

$$\sum_{i,j} I^{lp(x,y)}_{i,j,w} \le 1, \quad \forall (x,y),\ w \tag{3}$$

As such;

$$\sum_{w=0}^{W-1}\sum_{x} I^{lp(x,y)}_{i,j,w}\, l^{(x,y)} - \sum_{w=0}^{W-1}\sum_{x} I^{lp(y,x)}_{i,j,w}\, l^{(y,x)} = I^{lp}_{i,j}, \quad y = j \tag{4}$$

$$\sum_{w=0}^{W-1}\sum_{x} I^{lp(x,y)}_{i,j,w}\, l^{(x,y)} - \sum_{w=0}^{W-1}\sum_{x} I^{lp(y,x)}_{i,j,w}\, l^{(y,x)} = -I^{lp}_{i,j} \quad y = i \tag{5}$$

$$\sum_{w=0}^{W-1}\sum_{x} I^{lp(x,y)}_{i,j,w}\, l^{(x,y)} \quad \sum_{w=0}^{W-1}\sum_{x} I^{lp(y,x)}_{i,j,w}\, l^{(y,x)} = I^{lp}_{i,j} \quad y = j \tag{6}$$

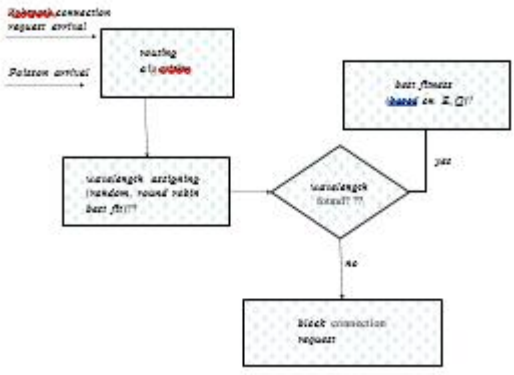

Fig. 7: Routing and wavelength assigning.

The block diagram in Figure 7 summarizes the wavelength assignment process. After identifying a potential wavelength, it is then evaluated to ensure optimal performance, considering both energy efficiency and path quality in relation to PLIs levels. The quality factor Q, used to characterize PLIs, will be defined and discussed in the following section. The upcoming sub- sections will provide a brief overview of these two evalua- tion criteria.

B) PLIs and Q-factor Measurements

The Q-factor is considered the most appropriate measure- ment for routing algorithms among the various optical per- formance metrics available as it exhibits a strong correla- tion and similarity with the BER [21], [22]. The equation below best illustrates the connection between the Q-factor and the BER.:

$$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (7)$$

where,

$$Q = \left(\frac{I_1 - I_0}{\sigma_1 + \sigma_2}\right)$$

I_1 and I_{01} are the mean photocurrent values of high and low signal levels respectively. σ_1 and σ_o are the standard deviations of high and low signal noise levels respectively.

Incorporating the Q-factor into the proposed resource allocation framework was done by drawing from various sources, including research in [23] that considers the effects of both XT and FC noises. We have developed a model in this section that considers various PLIs, including PMD ASE, XT, CD, FC, XPM, FWM, and SPM. The detailed expression for this model is provided in the following equation.:

$$Q_d = [EyePenalty] \times [NoisePenalty] \times Q_s \quad (9)$$

Qd is the connection destination Q-factor value, Qs is the connection source Q-factor value.

$$EyePenalty = \left(\frac{\langle I1 \rangle_d - \langle I_0 \rangle_d}{\langle I1 \rangle_s + \langle I_0 \rangle_s} \right) \qquad (10)$$

I1 d and I2 d are the mean photocurrent values of high and low signal levels at the connection destination respectively.

I1 s and Io s are the mean photocurrent values of high and low signal levels at the connection source respectively.

$$NoisePenalty = \left(\frac{\sigma_{1,s} + \sigma_{0,s}}{\sigma_{1,d} + \sigma_{0,d}} \right) \qquad (11)$$

$\sigma_{1,s}$ and $\sigma_{0,s}$ are the standard deviations of high and low signal noise levels at the connection source respectively.

$\sigma_{1,d}$ and $\sigma_{0,d}$ are the standard deviations of high and low signal noise levels at the connection destination respectively.

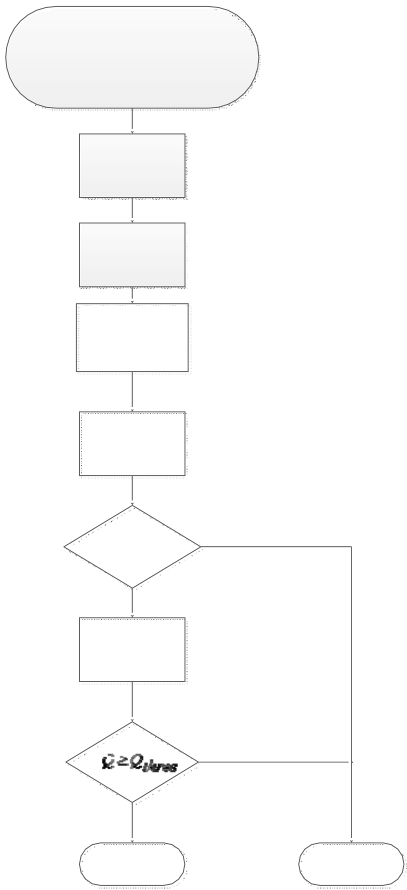

Fig. 8: Flowchart of the proposed algorithm

The penalties related to eyes are caused by CD, PMD, and FC impairments, while the penalties related to noise are caused by XT, ASE, SPM, XPM, and FWM impairments. It's worth noting that the variances of XT, ASE, SPM, XPM, and FWM for a lightpath can be calculated as the sum of the individual electrical variances of the links within the entire lightpath.

The proposed model consists of three main stages. In the initial stage, all relevant information about traffic requests and network characteristics is gathered, including optical channel characteristics, network topology, and capacity, as well as traffic characteristics such as bitrate and lightpath demands. Link costs are then determined based on this in- formation and will be considered during the path selection process. The second stage involves path and wavelength assignments, with the model proposing the shortest-widest path (SWP) and first-fit with ordering (FFwO) schemes. A set of k-shortest paths for each connection request is identi- fied, and an ILP optimization problem is solved to mini- mize network costs. The final stage validates the lightpaths generated in the second stage using the analytically modeled Q-factor, which accounts for physical layer impairments. If a candidate lightpath meets the predefined signal quality requirements and encompasses all specified im- pairments, a connection is established.

If the proposed lightpath signal quality fails to meet the requirements and/or does not consider the effects of physi- cal impairments, the connection is blocked. Figure 8 pro- vides an overview of the algorithm in flow chart form.

C) Energy-Efficiency

An ideal objective would involve creating a network that is both energy efficient and flexible. In this section, we will provide a brief overview of an energy-efficient and flexible Transparent OTN model. Our proposal involves assigning logical network connections to physical links through mul- tihopping in the networks. The assumptions made are as follows.:

- m and n represent the physical nodes in the net- work, and i and j represent the logical nodes in the virtual network topology.
- (s, d).-denotes the source (s)and destination (d) nodes.
- G(V , E) is the network's a physical topology comprising a set of V nodes interconnected by E unidi- rectional links.
- $T = [\wedge_{s,d}]$ indicates the traffic matrix forecast with demand $\wedge$s,d between a given (s, d) pair.
- $R = \phi_1, \phi_2, \ldots \phi_k$ is a set of available channel rates .
- W - denotes the number of wavelengths supported per fiber, $\lambda = w = [1,2,3,\ldots W]$.
- Er,k is the average energy cost of regenerator with rate ϕk .
- ER,k -average energy per TPND with rate ϕk .
- Ep -average energy cost of electronic processing.
- Lm,n is the length of the fiber between nodes m and n
- Am,n is the average number of amplifiers on a physi- cal link (m and n).
- Pm,n is the set of lightpaths passing through the link

(m and n).

- $F_{m,n}$ is the variable that denotes the number of fibers on a link (m and n).
- $f_{i,j}$ denotes the volume of traffic from source to destination on lightpath (i, j).
- Z_j is an integer that represents the amount of data that is transported by lightpaths that terminate at node j .

We also make the assumption that there are no wavelength converters available and that various line rates have varying optical reaches. The model is further characterized by the use of the parameters listed below:

- $l_{i,j,k,\lambda}$ represents the lightpath between (i, j) node pair in the logical topology at rate ϕ_k over λ.
- $\alpha_{i,j,k,\lambda}$ stands for the feasibility of lightpath estab- lishment for a given lightpath $l_{i,j,k,\lambda}$ between i and j nodes at rate ϕ_k for wavelength λ. The feasibility is based on the comparison with an accept- able preset threshold Q-factor.
- $X_{i,j,k,\lambda}$ is a variable that represents the number of lightpaths on link (i, j), and thus should be an integer.

Objective:

$$\text{minimize: } 2 \times \sum_{\lambda}\sum_{i,j}\sum_{k} X_{i,j,k,\lambda} E_{t,k} + \sum_{m,n} A_{\min} * F_{\min} + \sum_{j} Z_j * E_p \qquad (12)$$

The equation (12) aims to minimize energy usage within the network. In this equation, the first part calculates the overall energy consumption by TPNDs across the entire network. The second part computes the energy consumption by all amplifiers currently in use. As previously defined, "n" denotes the total number of optical fibers needed to handle the traffic. The final part of the equation represents the energy costs incurred by electronic components in op- eration at intermediate nodes for all traffic volume.

Equation (12) is subject to the following constraints:

$$\sum_{\lambda}\sum_{k} \phi_k * X_{i,j,k,\lambda} * \alpha_{i,j,k,\lambda} \geq \sum_{s,d} f^{s,d}_{i,j} \quad \forall(i,j) \qquad (13)$$

In other words, equation (13) represents constraints due to capacity that hinder the traffic demands per logical link (i, j).The wavelength-continuity constraint is represented by;

$$\sum_{(i,j)\in P_{m,n}} \sum_{k} X_{i,j,k,\lambda} * \alpha_{i,j,k,\lambda} \leq F_{m,n} \quad \forall(m,n), \ \forall\lambda \qquad (14)$$

Equation (14) guarantees that each wavelength is only as- signed to a single lightpath connection. To maintain a bal- ance between incoming and outgoing traffic at all nodes except for the source and destination nodes, we need to ensure that:

$$\sum_{j} - \sum_{j} = \begin{cases} \lambda^{s,d} & \text{if } s = 1 \\ & \text{if } d = j \\ 0 & \text{otherwise}, \ \forall i, \ \forall (s,d) \end{cases}$$

The aggregation of traffic flow that requires electronic processing at each node we can write;

$$Z_i = \sum_{s,d} \sum_{i} f_{i,j}^{s,d} \quad \forall i \neq a \qquad (10)$$

In brief, when a new lightpath connection request is received, it will be assessed considering both the awareness of available optical fiber paths and the energy efficiency. First, a group of the shortest potential paths from the source to the destination is determined. Then, it is verified whether the desired wavelength line rates and Q threshold are contiguous. If feasible, the energy consumption along the potential end-to-end light paths (Metric_EC) is calculated. This includes the combined energy consumption of the transponders (ECTRNDS) and that of data carriers.(ECtrans)

$$EC_{trans} = number\ of\ \text{wavelength carriers} \times \text{EC}_{\text{single carrier}} \qquad (17)$$

$$EC_{TPNDS} - number\ of\ \ TPNDs \times EC_{TPND} \qquad (18)$$

$$Metric\_EC = EC_{trans} + EC_{TPNDS} \qquad (19)$$

The allocation scheme follows the algorithm provided below. It specifies two distinct bands with a guard band between them. The search in the first waveband (10Gb/s) proceeds from left to right in ascending order, while the search in the second band (40 and 100 Gb/s) starts from right to left in descending order, allowing for wavelength shifts within a guard band . For each lightpath connection request, all potential k-shortest paths are calculated and evaluated for all possible line rate combinations. The list is then sorted based on energy consumption (Metric_EC) and comparisons. The flexible nature of the Optical Transport Network allows for new flow requests to be accommodated on an existing live lightpath connection. This can involve grooming the additional required capacity on the existing connection or augmenting the current flow's capacity. Should grooming not be feasible, it becomes necessary to provision additional capacity on the existing connection(s). Once again, the various permutations of line rates are computed and then arranged in order of energy efficiency and Quality of Transmission (QoT) (Q factor). It's important to note that the Q evaluation may be omitted if the same previously evaluated end-to-end path is utilized.

Algorithm I: RWA New lightpath connection demand

```
LowestMetric PC = 0
compute k candidate paths s,d; (k − shortest paths)
publish all line rates sets on the shorest path (reach ≥ path length)
for publish_ascending order [], line rates based on Metric + EC;
for publish_ascending order [], line rates based on Q^lp ≤ Q_threshold;
determine requested number of wavelengths wavelength/line speed)
while published list ≠ 0;
for each candidate path
if _true (transparent reach ≥ path length) & &(Q^lp ≤ Q_theshold)
if _10G in line rate set)
   search for allavailables wavelength setsc on 1st of links (s,d)
      if allocation = FALSE
search for all availables wavelength setsc by moving Δf to LEFT
    end
end
if allocation = TRUE
        Calculate_Metric_EC
   if (Metric_EC < Lowest_Metric_EC) or (Lowest_Metric_EC == 0)
      Lowest_Metric_PC = Metric_PC
        Save → MOst_Efficient_Allocation
                  end
                end
              end
           end
if Lowest_Metric_PC == 0
break
else
remove considered sets from list
end
end
if Most_Efficient_allocation exists
wavelength assignment for path = most_Efficient_allocation = true
else
     lightpath connection = block

     end
```

Should the new extra bandwidth allocation not be possi- ble, (by not matching any of the newly listed permuta- tions), a new lightpath connection establishment is ex- plored.

Algorithm II: additional bandwidth request

```
lightpath connection = block
Explore new lightpath establishment (Algorithim I)
else
if (requested BW ≤ residual lightpath BW) = TRUE
(Grooming : serve the demand using this residual lightpath BW)
else
acquire current avilablelighpath line rates
list permuatations for new demand request :
subject to : Q ≤ Qthreshold; trans_each ≥ path reach
for publish_ascending order [], line rates based on Metric_EC;
for publish_ascending order [], line rates based on Q^lp ≤ Qthreshold;
while published list ≠ 0;
compute number of additional wavelengths required :
compute number of wavelength to release if necesary
if ( extra 10G necessary + extra 40G/100G necessary) == 0
allocation possible
else
if (extra 10 G necessary) == TRUE
acquire current avilablelighpath line rates
search for allavailables wavelength setsc on 1st of links (s,d)
search for all availables wavelength setsc by moving Δf to LEFT
  end
end
if (extra 10 G necessary) == TRUE
search for all availables wavelength setsc by moving Δf to LEFT
    end
  end
end
if allocation = TRUE
  if (shifting wavelength in 2nd band necessary)== TRUE
40G ⇔ 100G or vice versa
end
  if ( wavelength releasing necessary) == TRUE
release accordingly
end
  if ( wavelength addition necessary ) == TRUE
assign accordingly
end
```

```
break
   end
end
if (allocation possible == FALSE
Explore new lightpath establishment (Algorithim I)
      end
   end
end
```

4. Performance Analysis

In this model, the Pan-European Network is utilized to test its suitability and precision. The network consists of 16 nodes and 23 bidirectional fiber links. Connection requests are assumed to follow a Poisson distribution, and the nodes do not possess wavelength conversion capabilities. Addi- tionally, the model does not consider protection or regen- eration. To address the routing sub-problem, the shortest- widest path (SWP) algorithm is utilized, while the wave- length assignment sub-problem is solved using the First-fit with Ordering (FFwO) algorithm.

Upon receiving a connection request, the system identifies the shortest and least congested path and processes the re- quests in their order. Then, the FFwO algorithm is used to select an available wavelength from the pool of available wavelengths.

Each candidate path's Q-factor is calculated and those paths that have a Q-factor that is lower than a pre-set threshold (Qthres) are blocked.

We chose the whole network to consist of SSMF with a dispersion, $D = 12 \quad ps/nm/km$ an attenuation constant of $\alpha = 0.25 dB/km$ and a nonlinearity constant of $\gamma = 1.5(W / Km)$. We also assume a communication channel plan a maximum of 40 wavelengths per link spaced at 50 GHz . The threshold q-factor is configurable and overall noise figure is set at 5 dBw.

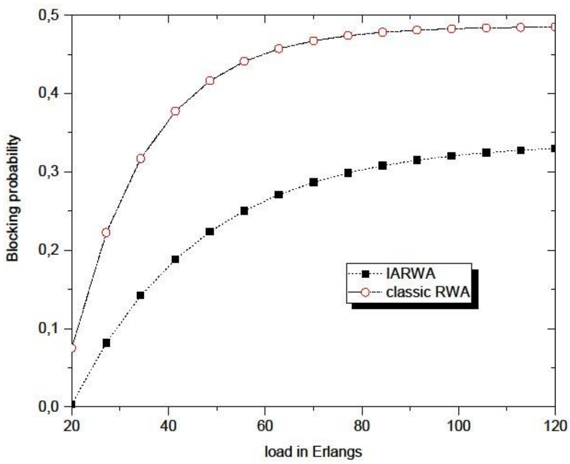

Fig. 9: The relationship between blocking probability and network load for the Pan-European

Network

When comparing the blocking probabilities of the classic RWA algorithm and our proposed IA-RWA algorithm in the Pan-European Network topology, Figure 9 shows that they perform similarly at low network loads but distinctly at high loads. Additionally, Figure 4 demonstrates that our proposed IA-RWA algorithm significantly reduces blocking probability compared to the classic RWA algorithm in the MESHNET topology, showing improved network performance in this setting. This indicates that our model can effectively enhance the performance of both regular and fairly large irregular networks under high loads. Overall, our pro posed algorithm clearly outperforms the classic one, leading to improved network performance.

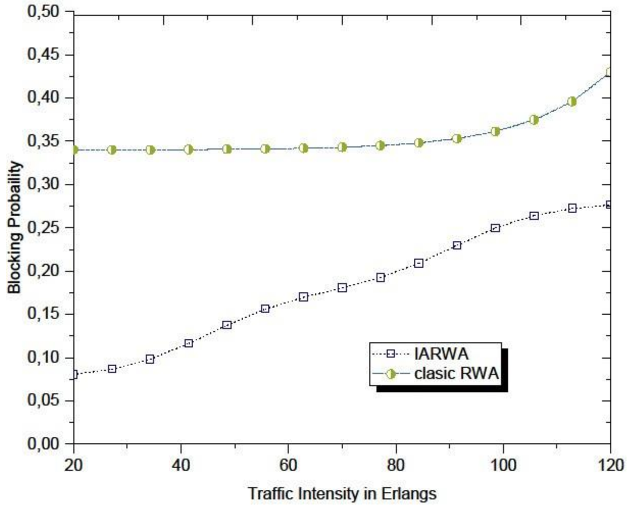

Fig. 10:. Relationship between blocking probability and network load for the MESHNET topology

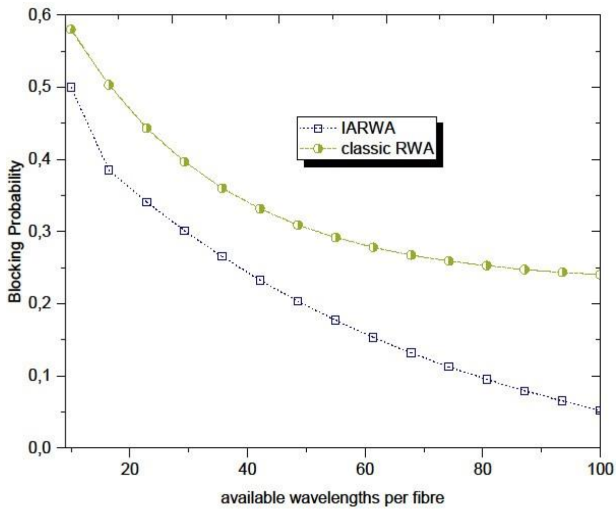

Fig. 11: Relationship between blocking probability and number of wave- lengths per fiber

The results from both the standard RWA and our IA-RWA algorithms are depicted in Figure 11, illustrating the changes in blocking probability and the available number of wavelengths per fiber. Our proposed model demonstrates lower blocking rates, particularly when the available wave- lengths are limited. As the number of wavelengths ap- proaches a specific threshold (60), the blocking probability stabilizes, indicating that physical impairments significantly impact network blocking rates. In Figure 12, we observe the correlation between Q-factors and the ratio of existing lightpaths for the shortest path (SP) combined with first fit (FF) algorithm, as well as for the SP with FFwO algorithm. With a traffic load of 10 Erlangs, a substantial portion of lightpaths using the SP with FF algorithm have a Q-factor below 14, in contrast to the SWP, FFwO algorithm where a significant portion of existing lightpaths have a Q-factor above 14. It is evident that the SWP, FFwO algorithm re- sults in better utilization of network resources and satisfac- tory physical performance.

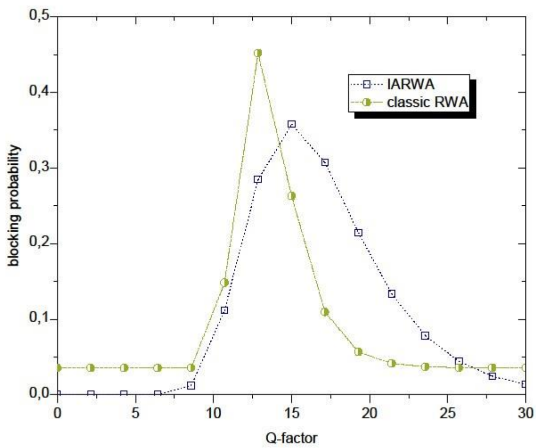

Fig. 12: Relationship between existing lightpaths and Q-factors

The results presented in Figure 13 indicates that the average processing time of the IA-RWA algorithm is greater than that of the pure RWA algorithm.

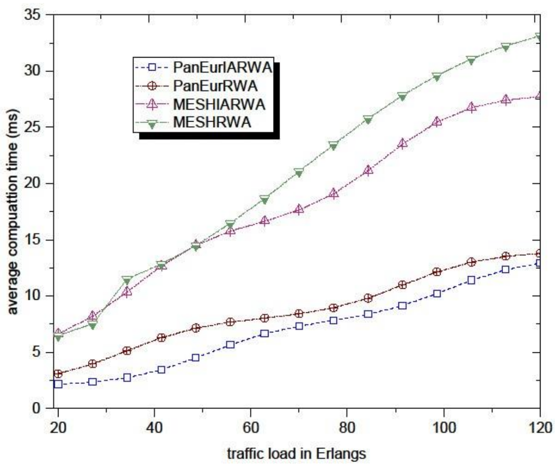

Fig 13:. Variation of average computation time with network load

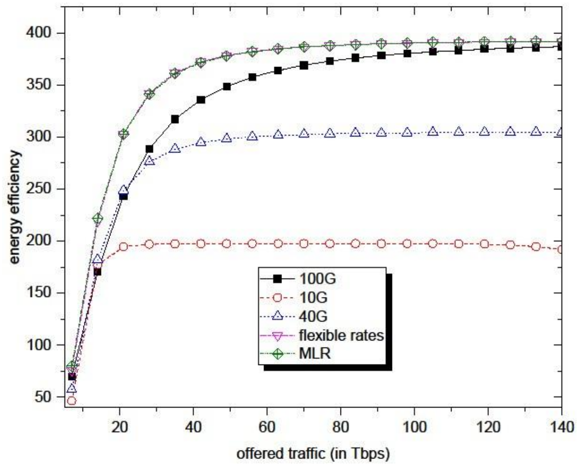

Fig. 14:. Energy efficiencies comparisons

The reason for this could be that our IA-RWA algorithm considers impairments when making decisions. The algo- rithm gathers information on impairment effects on the sig- nal during transmission, and then evaluates the signal qual- ity against a set threshold value. This approach increases computation time, so there's a balance between achieving high quality of transmission and computational time. Fur- thermore, it's noted that the computational time for classic RWA is similar regardless of network topology, especially at low network loads.

In addition, we assess the energy efficiency of the sug- gested resource allocation framework through simulation. This involves analyzing parameters such as the service blocking ratio and energy efficiency. The service blocking ratio refers to the proportion of light path requests that were prevented compared to the total number of requests. This ratio is essential for evaluating overall network energy us- age, as some blocked traffic would have already consumed a considerable amount of energy and resources before being blocked.

$$B = \frac{\sum unsuccesful\ \ requests(blocked)}{\sum registered\ \ number\ \ of\ requests\ \ in\ the\ \ network} \qquad (20)$$

Likewise the energy efficiency is an indicator of the amount of energy well spent in servicing the end to end lightpath connections

$$\eta_{energy} = \frac{\sum data\ \ traffic}{\sum Energy\ \ spent\ \ within\ \ the\ network} \qquad .(21)$$

It is the ratio of the traversed data traffic to the total energy consumption of the network.The following text needs to be remembered: We are comparing different network operation methods, such as single line rate (SLR), mixed line rate (MLR), with flexible-grid based OFDM. The traffic load gradually increases from low to high. The energy efficiency performance for these methods is shown in Figure 14.

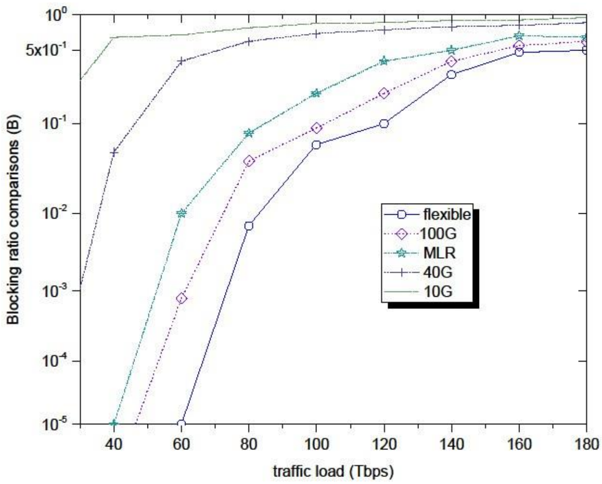

Fig 15: Service ration blocking comparisons

The graph indicates that MLR and flexible OFDM are comparable and outperform the three SLR cases of 10G, 40G, and 100G. Their superior energy efficiency is due to their ability to adjust to the actual demand transmission rates. Among the three cases, the 100G network operation shows relatively better energy efficiency at high traffic loads as its channels will always be at full capacity. The service blocking ratio of the overall network also directly affects energy efficiency. A high blocking ratio means that the network resources needed to serve a particular traffic load will be inflated, resulting in lower energy efficiencies.

In Figure 15, it is evident that using flexible OFDM for operation will lead to lower service blocking when compared to the 100G and MLR scenarios.

5. Concluding Remarks

The paper introduces a Q-factor tool that accounts for vari- ous physical layer impairments. Through simulations, the tool's performance is compared with traditional approaches, showing that it outperforms them. The paper also proposes an analytical technique for computing blocking probabili- ties in transparent optical transport networks with physical impairments, supported by numerical examples and simula- tions. The model's performance is evaluated using QoT- aware and QoT-guaranteed RWA approaches in different networks, demonstrating its accuracy across various scenar ios. The results highlight the potential of flexible Transpar- ent TOCNs in achieving energy efficiency and high net- work link utilization, which could lead to significant cost savings.

References

1. M. Gomba, B. Nleya, A. Mutsvangwa and R. Chidzonga, "Evaluation of Wavelength Congestion in Transparent Optical Transport Networks," 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data

Communication Systems (icABCD), Durban, South Africa, 2020, pp. 1-5.

2. N. Amdouni and T. Aguili, "A new wavelength rerouting scheme with short service disruption period for dynamic traffic in WDM transparent optical networks with physical layer impairments consideration," 2016, 7th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications (SETIT), Hammamet, 2016, pp. 378-380.
3. Y. Miyamoto and R. Kawamura, "Space Division Multiplexing Optical Transmission Technology to Support the Evolution of High-capacity Optical Transport Networks", NTT Technical Review, Volume. 15, Number 6 , June 2017.
4. T. Morioka, M. Jinno, H. Takara and Hirokazu Kubota, "Innovative Future Optical Transport Network Technologies", NTT Technical Review, Volume. 9 Number 8, Aug. 2011.
5. K. Guan et al., "Towards Realistic High-Speed Train Channels at 5G Millimeter-Wave Band—Part II: Case Study for Paradigm Implementation," in IEEE Transactions on Vehicular Technology, vol. 67, no. 10, pp. 9129-9144, Oct. 2018, doi: 10.1109/TVT.2018.2865530.
6. I. Tomkos, E. Palkopoulou and M. Angelou, "A survey of recent developments on flexible/elastic optical networking," 2012 14th International Conference on Transparent Optical Networks (ICTON), Coventry, 2012, pp. 1-6.
7. A. Lometti, S. Frigerio and L. Ronchetti, "Extending the scope of OTN to access and metro networks," 2017 19th International Conference on Transparent Optical Networks (ICTON), Girona, 2017, pp. 1-4.
8. ITU-T G.709/Y.1331 , Interfaces for the Optical Transport Network (OTN) Telecommunication Standardization Sector of ITU (12/200
9. K. Shintaku, S. Kuwahara, and S. Kobayashi, "Trends in Standardization of Mapping and Multiplexing Technologies for Optical Transport Networks", NTT Technical Review, Volume 18, Number 12, Dec. 2020.
10. S. Azodolmolky, M. Klinkowski, E. Marin, D. Careglio, J. S. Pareta, and I. Tomkos, "A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks," Computer Networks, vol. 53, no. 7, pp. 926–944, May 2009.
11. A. Muhammad, "Planning and provisioning strategies for optical core networks," PhD, Linkoping University, Sweden, 2015.
12. E. Varvarigos, "An introduction to routing and wavelength assignment algorithms for fixed and flexgrid," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, The Optical Society, 2013.
13. Y. Zhai, Y. Pointurier, S. Subramaniam, and M. Brandt-Pearce, "Performance of dedicated path protection in transmission- impaired DWDM networks," in 2007 IEEE International Conference on Communications, Institute of Electrical and Electronics Engineers (IEEE), 2007.
14. S. Pachnicke and P. M. Krummrich, "Constraint-based routing in path-protected translucent optical networks considering fiber nonlinearities and polarization mode dispersion," in Optical Transmission, Switching, and Subsystems VI, SPIE-Intl Soc Optical Eng, 2008.
15. X. Yang, L. Shen, and B. Ramamurthy, "Survivable lightpath provisioning in WDM mesh networks under shared path protection and signal quality constraints," Journal of Lightwave Technology, vol. 23, no. 4, pp. 1556–1567, Apr. 2005.
16. Y. Pointurier, "Cross-layer design of all-optical networks incorporating crosstalk effects," PhD, University of Virginia, 2006.
17. S. Pachnicke, T. Paschenda, P. Krummrich, and Dortmund, "Assessment of a constraint-based

routing algorithm for translucent 10Gbits/s DWDM networks considering fiber nonlinearities," Journal of Optical Networking, vol. 7, no. 4, pp. 365–377, Apr. 2008. [Online].Available: http://www.opticsinfobase.org/abstract.cfm?URI=JON-7-4-365. Accessed: Jun. 15, 2015.

18. E. Salvadori et al., "Signalling-based architectures for impairment-aware Lightpath set-up in GMPLS networks," in IEEE GLOBECOM 2007-2007 IEEE Global Telecommunications Conference, Institute of Electrical and Electronics Engineers (IEEE), 2007.
19. S. Azodolmolky, M. Klinkowski, E. Marin, D. Careglio, J. S. Pareta, and I. Tomkos, "A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks," Computer Networks, vol. 53, no. 7, pp. 926–944, May 2009.
20. Y. Li, L. Gao, G. Shen and L. Peng, "Impact of ROADM colorless, directionless, and contentionless (CDC) features on optical network performance [Invited]," in IEEE/OSA Journal of Optical Communications and Networking, vol. 4, no. 11, pp. B58-B67, Nov. 2012..
21. T. Ivaniga and P. Ivaniga, "Evaluation of the bit error rate and Q-factor in optical networks," IOSR Journal of Electronics and Communication Engineering, vol. 9, no. 6, pp. 01–03, 2014.
22. M. S. Hossain, S. Howlader, and R. Basak, "Investigating the Q- factor and BER of a WDM system in Optical Fiber Communication Network by using SOA," International Journal of Innovation and Scientific Research, vol. 13, no. 1, pp. 315– 322, Jan. 2015.
23. A. Jirattigalachote, "Provisioning Strategies for Transparent Optical Networks Considering Transmission Quality, Security, and Energy Efficiency," PhD, KTH Information and Communication Technology, Stockholm, Sweden, 2012.