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Restorability on 3-connected WDM Networks Under Single and Dual Physical Link Failures

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***Abstract*—This work studies the influence the network interconnection has over restoration techniques. The way physical links are distributed to interconnect network nodes has a great impact on parameters such as path distances when failures occur and restoration is applied. The work focuses on single and dual physical link failures restorability on WDM transport networks. This failure scenarios are tested over several 3-connected topologies, and studied in graph theory and network planning terms. In connection with the graphs, the resulting hop path distances and lengths are evaluated. In relation to network planning, the trade-off network length vs. performance of the different topological options is studied. The results show how 3-connected graphs could provide a reasonable trade-off between costs, link failure rates, and restored path parameters.**

I. Introduction

Communication networks are essential in our daily activities, and they are expected work properly at anytime providing high quality services. The reliability requirements are specially high for heavy traffic transport networks such as WDM backbone networks, where failures can cause significant profit losses [1].

Unavoidably, different types of failures occur in networks ranging from hardware malfunctioning to human errors. Among these, the relevance of cable cuts is specially significant for large area transport networks. Statistically, the frequency of cable cuts is directly proportional to their physical length [1] and [2]. Consequently, networks consisting of long links (>1000 km) constantly suffer this type of disturbances.

In this context, single link failures have drawn the attention of researchers, and lately, studies covering also two or more independent failures have arisen due to the mentioned relevance of communication network in our current society. Examples of these studies are [3], [4], or [5].

In order to support this type of failures there are two main groups of techniques : Protection and restoration [2]. When a failure occurs, protection is capable of providing an alternative pre-configured disjoint route for any affected source-destination pair. On the other hand, in the case of using restoration, when a failure is detected in a path between nodes, a new path is established, avoiding the point of failure. No pre-configured disjoint path is provided.

This work focuses on restoration applied in WDM networks when links fail. More specifically, we study the restoration properties for single and dual link failures in 3-connected topologies, from both graph theory and network planing points of view. In such scenarios, 3-connected graphs are desirable since they are fully capable of supporting two simultaneous failures without loss of any source-destination connection [6].

These topologies are used in a case study by designing the interconnection of the 16 nodes belonging to the NSFNET network. The topologies are three well-known structured topologies, Double Ring DR, Chordal Ring with chord length 5 $CR(16,5)$, and Chordal Ring with chord length 7 $CR(16,7)$ [7]. The interconnection is designed by minimizing the total network's length for each studied topology. In addition, an overall unstructured 3-regular and 3-connected interconnection also minimizing its length is studied, $3-CON$. All these, as the $NSFNET$ network have 24 links.

The procedure to study the consequences of applying restoration is to systematically remove a link (or a link pair in the case of dual failures) at a time. Then, restoration is applied when necessary, and the paths between nodes are evaluated in terms of hop count and physical length. Also, the number of restored paths per failure can be quantified.

Therefore, the main goal of this work is to analyze the restoration properties of 3-connected topologies on WDM networks. Specifically, the influence of how the links are distributed to interconnect nodes over failure situation is quantified in terms of path parameters, and cost trade-offs. Consequently, the topological design and the interconnection decision process for this type of networks can also take into account restorability properties.

The rest of the document is as follows: Section II summarizes the related work, and lists some important concepts and definitions. Section III introduces the methodology followed to carry out the experiments. Section IV presents the case study and its results. Finally Section V summarizes the conclusions of this work.

II. Background

A. Definitions

The following paragraphs introduce important concepts and definitions in relation to this work.

Set of nodes and set of links: S_N corresponds to the set of nodes to interconnect, and S_L is the set of links used for this interconnection. Each link has a physical length associated to it.

Single failure is referred to the time when there is one and only one link unavailable in the network.

Dual failure is referred to the time when there are two and only two simultaneous links unavailable in the network.

k-connected graph: A graph is k-connected when any $k-1$ elements (nodes or links) can be removed from the network and still have a connected graph.

Physical link disjointness: In this work all the links are physically disjoint from each other, they do not share any trenches.

Path: It is referred to as the set of traversed nodes when information is flowing between a pair of nodes.

Length and Distance: Define two different concepts in this paper. Length is always used in physical terms (km) and distance is always used in transmission path terms (hop count). For example, the path length between A and B is 304 km, and the path distance between A and B is 5 hops.

Routing: Two types of routing are applied to the studied scenarios, *Minimum Hop,* MH and *Minimum Length,* ML.

In MH the information between nodes is routed using the path with the lowest hop count. In case of multiple selection options, the priority is given to the one with the shortest length.

In ML the information between nodes is routed using the path with the lowest physical length.

Restoration procedure: When a path is disrupted by a failure, this is not notified to the source node. Instead, the information is routed using the primary path until the failure is reached. Then, the path is modified surrounding the failure and reaching the destination [2]. This newly calculated path from the failure link also follows the routing conditions of minimum hop or length.

B. Related work

Restoration

Restoration has been widely used and implemented in many different networking scenarios. Examples of these can be found in the context of optical networks in [8], or in connection with wireless sensor networks in [9], among others. More specifically, there are several studies in relation to dual failures and restoration in WDM, these are three examples: [10] deals with dimensioning optimization to avoid blocking of demands due to the lack of sufficient capacity, [11] proposes protection and restoration methods for handling dual link failures, and [12] studies the trade-off between capacity and robustness of a proposed restoration algorithm.

However, all these studies consist of algorithmic evaluations or dimensioning optimizations, but do not study restoration and dual link failures from a graph and network interconnection point view.

Protection analysis

Previously, the authors have studied in [13] the effect of single and dual link failures in similar scenarios applying protection. The main characteristic of 3-connected topologies is that even under dual failure conditions, there are connections available between any pair of nodes. Consequently, the use of these topologies against the traditional 2-connected $NSFNET$ implies great benefits under dual failure conditions.

A priori, the benefit is not that evident when applying restoration, as the paths between nodes are more dynamic in failure situations. Therefore, the study of restoration over these 3-connected topologies will complement and expand the work already done in relation to the effect of physical link failures on WDM networks.

III. Methodology

The procedure followed in order to study the restoration properties is described in the following paragraphs.

Firstly, it is important to explain the scenarios used to carry out the experiments. As mentioned above, different interconnection options are evaluated. More concretely, four 3-connected topologies, three structured: DR, $CR(16, 5)$, and $CR(16, 7)$, and one unstructured 3-regular topology, $3-CON$. Each of these topologies is designed minimizing the total network length. For this type of large area networks, to minimize the network's total length also implies a minimization of the total deployment cost, due to the high trenching cost compared to the fiber or facilities costs. The structured interconnections are extracted for the results in [14], the unstructured from [15], and a complete explanation on the interconnection decision procedure can be found in [16].

Table I presents the length and the yearly link failure rate of the evaluated topologies including the $NSFNET$ as a reference. The failure rate is calculated using a mean time to fail of 500 FIT/km of link [1].

Top.	$3-CON$	DR	$CR(16,7)$	$CR(16,5)$	$NSFNET$
Km	20577	23795	25339	28967	23866
Fail./y	90.1	104.2	111	126.9	104.5

TABLE I
LENGTHS AND LINK FAILURE RATES

A. Procedure

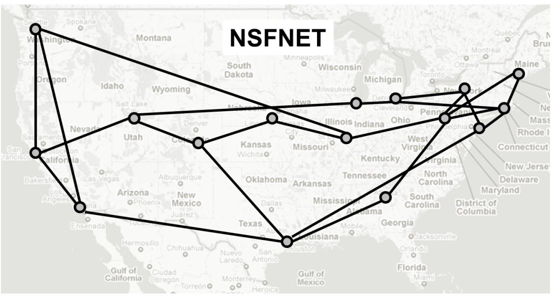
As introduced above, the procedure to evaluate restoration in a deterministic way is to systematically remove from the graphs one link in the case of single failure or a pair of links in the case of dual failure at a time. Then the relevant path parameters are calculated for each link or link pair removal, covering all possible single and dual link failures.

In this way, the restoration path properties can be evaluated, and the consequences of link failures can be estimated from a graph theory perspective.

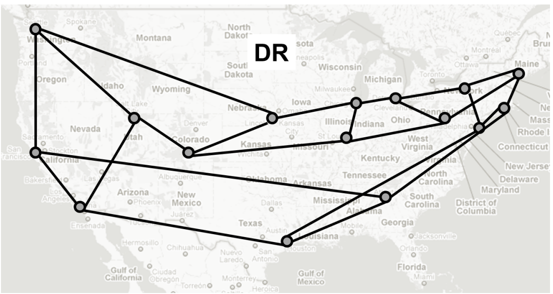
B. Parameters

The following list summarizes the parameters used to evaluate the different interconnection options under single and dual failure situations.

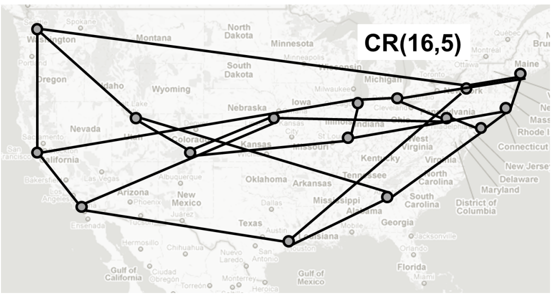
The impact of failures over the paths is evaluated in terms of average number of restored paths per failure, average hop path distance per failure, and average path length per failure. The contributions of each failure must be weighted accordingly as the frequency of the failures of each link is considered proportional to its physical length. In this way, the results for failures of longer links will have more influence on the averages than for shorter links (that fail less frequently). The



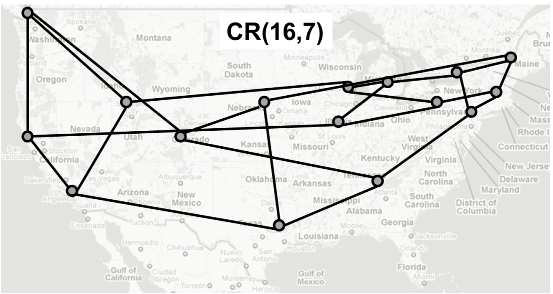
(a) NSFNET



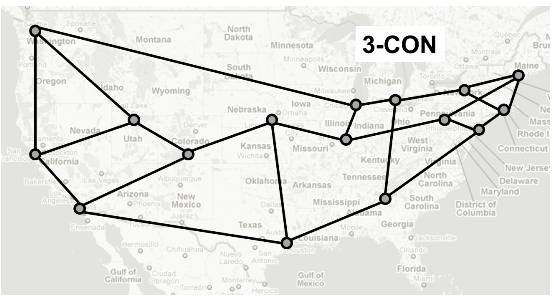
(b) DR



(c) CR(16,5)



(d) CR(16,7)



(e) 3-CON

Fig. 1. Interconnection Solutions

weights are given following Eq. 1 (a) for single failures (w_i) and Eq. 1 (b) for dual failures (w_{ij}). l_i is the length of link i, l_{nt} the network's total length, and l'_{nt} the sum of the length of all the possible combinations of two link pairs product.

$$w_i = \frac{l_i}{l_{nt}}\ (a) \qquad w_{ij} = \frac{l_i \cdot l_j}{l'_{nt}}\ (b) \tag{1}$$

Weighted average restored paths, $WAFP$:

It presents the average number of affected/restored connections affected by failures, weighted based on the mentioned length of each failure. The calculation is described by Eq. (2), AF^i being the number of restored paths under failure of link i and AF^{ij} under failure of links i and j.

$$\begin{aligned} WAFP^s &= \sum w_i \cdot AF^i \ \ \forall i \in S_L \\ WAFP^d &= \sum w_{ij} \cdot AF^{ij} \ \ \forall i,j \in S_L \end{aligned} \tag{2}$$

Weighted average distance, WAD:

Following the same principles, the weighted average path distance for single failures (WAD^s) is presented in Eq. (3), $hp^i(x,y)$ being the hop count of the path between nodes x and y under failure of link i. This path can be the primary, or restored path if the primary is affected by the failure. Also, the procedure is similar in the dual failure cases (WAD^d).

$$WAD^s = \sum w_i \cdot \frac{hp^i(x,y)}{N \cdot (N-1)} \ \ \forall i \in S_L, \forall x,y \in S_N \tag{3}$$

Weighted average length, WAL:

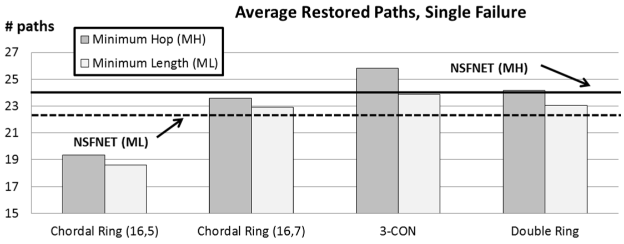
The weighted average path length for single failures (WAL^s) is presented in Eq. (4), $lp^i(x,y)$ being the length of the path between nodes x and y under failure of link i. The procedure is similar in the dual failure cases (WAL^d).

$$WAL^s = \sum w_i \cdot \frac{lp^i(x,y)}{N \cdot (N-1)} \ \ \forall i \in S_L, \forall x,y \in S_N \tag{4}$$

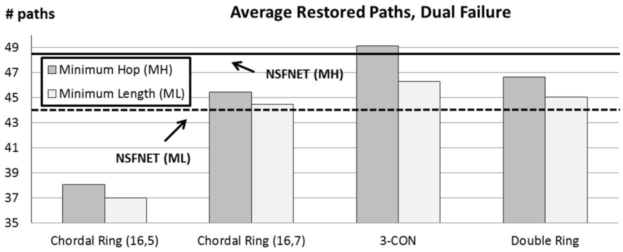
Parameters vs. network length normalized over $NSFNET$:

Usually, for this type of networks, the main deployment expense is related to trenching and digging, more than 80 % of the total. This is directly proportional to the length of the links interconnecting the nodes, and consequently the physical length of the network can be considered as a representation of the deployment expenses. In addition, the yearly link failure rate is also proportional to the length of the network, as depicted in Table I.

Based on these assumptions, the length of the different topological solutions for the interconnection is linearly used, in order to quantify the trade-off between cost and failure rates over any other parameter. Moreover, the values are normalized over the same values obtained for the $NSFNET$ network. In this way, the resulting values above 1 present better trade-off compared to $NSFNET$ and values below 1 the opposite. Eqs. (5) and (6) illustrate an example of the calculations for the trade-off length vs. WAD^s, T^x_{WAD} being the trade-off calculated for topology x and $NORM()$ the normalized

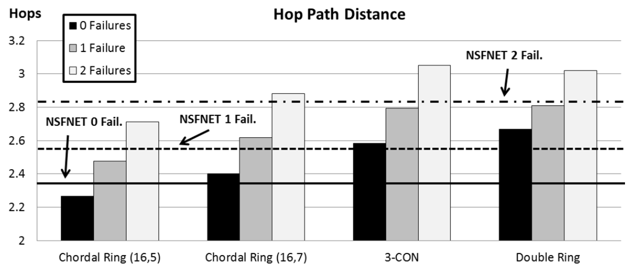


(a) Single Failure

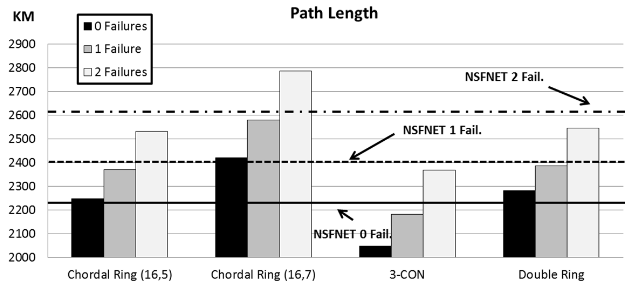


(b) Dual Failure

Fig. 2. Average Restored Paths per Failure



(a) Minimum Hop Routing, WAD



(b) Minimum Length Routing, WAL

Fig. 3. Path Analysis Results

values. For the rest of the studied parameters the procedure is exactly the same.

$$\mathrm{T}^{x}_{WAD^s} = \frac{WAD^s_x}{l^x_{nt}} \tag{5}$$

$$NORM(\mathrm{T}^{x}_{WAD^s}) = \frac{\mathrm{T}^{x}_{WAD^s}}{\mathrm{T}^{NSFNET}_{WAD^s}} \tag{6}$$

IV. Case Study

The case study consists of evaluating several interconnection designs for the 16 nodes of the well-known $NSFNET$. These interconnections are designed minimizing the total network length and following certain topological constraints, being all 3-regular and 3-connected.

Two analysis are performed, in order to evaluate the benefits of using the proposed interconnections, path and trade-off network length vs. performance analysis.

A. Path Analysis

In relation to the effect failures have on transmission paths, Fig. 2 illustrates the weighted average number of restored paths for the four studied topologies applying MH and ML routing. Fig. 2(a) for single failures and Fig. 2(b) for dual failures. The values for the $NSFNET$ are also displayed as a reference. In the dual failure case, this value corresponds to the sum of restored paths plus disconnected node pairs since $NSFNET$ is only 2-connected.

In all the topological options ML implies less restored paths on average per failure. $CR(16,5)$ is the best performing option for both routing schemes, and for ML $NSFNET$ is the second best option.

Fig. 3 presents the results in connection with path distances and lengths. Fig. 3(a) illustrates the weighted average path distance for the studied options applying MH. Fig. 3(b) illustrates the weighted average path length applying ML. In both figures the values are presented in the ideal case of no failures, single failures, and dual failures. Also, the obtained values for $NSFNET$ are displayed as a reference.

In relation to hop path distances, $CR(16,5)$ is the best performing option even better than $NSFNET$ in all the three cases: no failures, single failures and dual failures. None of the other options outperforms the $NSFNET$.

On the other hand, regarding path lengths, $3-CON$ presents the best results. Also, DR outperforms $NSFNET$ in all the cases, and $CR(16,5)$ in failure cases.

Based on these results, it is clear that $CR(16,5)$ is the best option among the studied, implying a significant improvement over $NSFNET$. However, this topology is the longest implying that it is the most expensive to deploy and with the highest yearly link failure rate.

B. Trade-off Analysis

In order to evaluate and compare the interconnections also taking into account their associated length, the same parameters, WAD, WAL, and number of restored paths are analyzed as normalized trade-off values. The calculations of these values are described in Section III-B. It is important to keep in mind that the trade-off value (T) for each parameter is normalized over the trade-off value of the same parameter for the $NSFNET$ network.

Fig. 4 presents the trade-off related to the number of restored path per failure, only the $3-CON$ option presents a clear benefit over the $NSFNET$. In the case of dual failures, only the pairs of nodes with a connection available were considered to obtain the values in the $NSFNET$. As this topology is only 2-connected, for some pairs under certain dual link failures, a connection cannot be established.

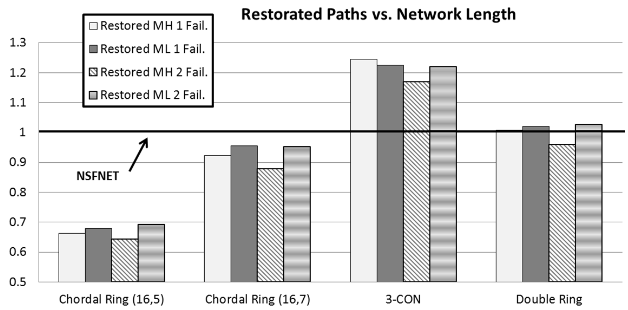
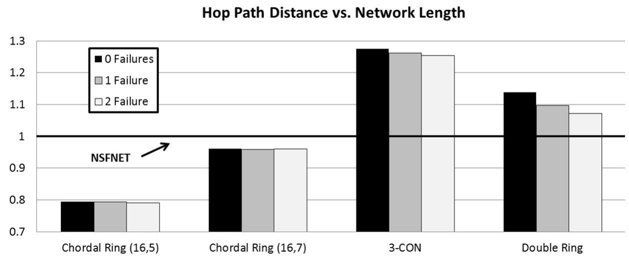
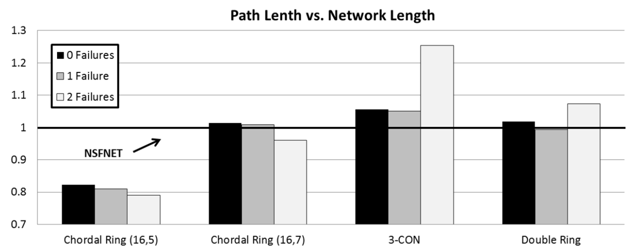


Fig. 4. Normalized Number of Restored Paths per Failure



(a) Minimum Hop Routing



(b) Minimum Lenght Routing

Fig. 5. Normalized Path Results

Fig. 5 illustrates the normalized results of the trade-off in connection with path distances and lengths. The main conclusion extracted is that again, the best option is the $3-CON$ solution. However, the DR option also outperforms the $NSFNET$ trade-off.

V. Conclusion

This paper studies the restorability of different 3-connected topologies over the well-know geographical scenario of the $NSFNET$ network. More specifically, the study covers single and dual physical link failures in optical transport networks. The study consists of a path and a trade-off analysis. The path analysis presents the results in terms of average restored paths, average hop path distance, and average path length when links failure. The trade-off analysis intends to provide a better comparison between the different topological options, relating these restorability parameters to the length of each solution, and by extension to the deployment costs and link failure rates.

The deployment of 3-connected topologies is always a better option than the $NSFNET$ in terms of dual failures support, since there is no possible chance of loosing connectivity between any pair nodes. Despite of this fact, some 3-connected topologies also outperform the $NSFNET$ in terms of average hop path distance, average path length, or average restored paths per failure.

The $CR(16,5)$ is the best among the studied options when comparing the absolute values of the studied restorability parameters. However, the consequence of obtaining the best performing topology in terms of restorability is to build a much longer network implying a higher deployment investment and link failure rate.

Instead, when considering the length of the network as a deployment cost and link failure rate measurement, and based on the proposed trade-off analysis, the $3-CON$ solution is the best suited when applying restoration.

The results obtained in this work, combined with other studies covering many different properties of 3-connected graphs applied to WDM networks might contribute to the inter-connection decision strategies for near future optical networks.

References

[1] M. To and P. Neusy, “Unavailability analysis of long-haul networks,” *IEEE journal on selected areas in communications*, vol. 12, January 1994.

[2] W. D. Grover, *Mesh-Based Survivable Networks, Options and Strategies for Optical, MPLS, SONET and ATM Network*. Prentice Hall PTR, 1st ed., August 2003.

[3] W. He and A. K. Somani, “Path-based protection for surviving double-link failures in mesh-restorable optical networks,” in *Proceedings of IEEE Globecom 2003*, 2003.

[4] L. Guo, L. Li, J. Cao, H. Yu, and X. Wei, “On finding feasible solutions with shared backup resources for surviving double-link failures in path-protected wdm mesh networks,” *J. Lightwave Technol.*, vol. 25, 2007.

[5] J. Doucette, M. Clouqueur, and W. D. Grover, “On the availability and capacity requirements of shared backup path protected mesh networks,” *Optical Networks Magazine*, 2003.

[6] R. Diestel, *Graph Theory (Graduate Texts in Mathematics)*. Springer, August 2005.

[7] J. M. Pedersen, *Structural Quality of Service in Large-Scale Network*. PhD thesis, Aalborg University, April 2005.

[8] R. Iraschko and W. Grover, “A highly efficient path-restoration protocol for management of optical network transport integrity,” *Selected Areas in Communications, IEEE Journal on*, vol. 18, pp. 779 –794, may 2000.

[9] J. Al-Karaki and A. Kamal, “Routing techniques in wireless sensor networks: a survey,” *Wireless Communications, IEEE*, vol. 11, pp. 6 – 28, dec. 2004.

[10] W. He, M. Sridharan, and A. K. Somani, “Capacity optimization for surviving double-link failures in mesh-restorable optical networks,” *Photonic Network Communications*, vol. 9, pp. 99–111, 2005.

[11] H. Choi, S. Subramaniam, and H.-A. Choi, “Loopback recovery from double-link failures in optical mesh networks,” *IEEE/ACM Trans. Netw.*, vol. 12, pp. 1119–1130, Dec. 2004.

[12] S. Lumetta, M. Medard, and Y.-C. Tseng, “Capacity versus robustness: a tradeoff for link restoration in mesh networks,” *Lightwave Technology, Journal of*, vol. 18, pp. 1765 –1775, dec 2000.

[13] J. M. Gutierrez, K. Georgakilas, T. Riaz, K. Katrinis, J. M. Pedersen, A. Tzanakaki, and O. B. Madsen, “Single and dual physical link failures stability effect on degree three wdm networks,” in *The 16th Asia-Pacific Conference on Communications Proceedings, APPC 2010*, 2010.

[14] J. M. Gutierrez, K. Katrinis, K. Georgakilas, A. Tzanakaki, and O. B. Madsen, “Increasing the cost-constrained availability of wdm networks with degree-3 structured topologies,” in *Transparent Optical Networks (ICTON), 2010 12th International Conference on*, pp. 1–4, 2010.

[15] J. M. Gutierrez, T. Riaz, and J. M. Pedersen, “Cost and availability analysis of 2- and 3-connected wdm networks physical interconnection,” in *Proceedings in ICNC 2012*, 2012.

[16] J. M. Gutierrez, T. Riaz, J. M. Pedersen, A. Patel, and O. B. Madsen, “Analytical model based on green criteria for optical backbone network interconnection,” *Elsevier Computer Standards and Interfaces*, vol. 33, pp. 574–586, November 2011.