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Cost and Availability Analysis of 2- and 3-Connected WDM Networks Physical Interconnection

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***Abstract*—Our future in personal and professional lives is becoming more attached to the evolution of communication technologies and their applications. Consequently, the way Next Generation Network are currently being planned and deployed, might have a great impact on common people depending on how networks are physically interconnected. Ideally networks should be cheap, reliable, flexible, and energy efficient, among other properties. However, some of these properties are contradictory, i.e. higher fault tolerant networks usually imply higher deployment costs. Therefore, the interconnection decision is a search for the best trade-off among the relevant parameters for the network. In this paper we analyze this trade-off by studying 2- and 3-connected graphs to be used as WDM (Wavelength Division Multiplexing) networks physical infrastructure. The experiments show how the way links are distributed to interconnect the nodes has a significant impact on the cost and availability of the network.**

I. Introduction

Network's physical interconnection may have a great impact on their performance [1]. Currently, networks are being deployed following the approach "best performance with minimum deployment investment". Depending on the kind of networks, this approach would lead to tree structured interconnection in access networks such as Fiber To The Home (FTTH) [2], or interconnected rings for Metropolitan or Wide Area Networks (MAN and WAN) [3].

The deployment of optical networks is usually expensive compared to wireless networks such as $3G$ or LTE [4]. In addition, future wired network should have a lifetime of 30-40 years in order to obtain the most benefits out of the high deployment expenses [5]. Therefore, these should be designed not only considering near future requirements but also mid and long term demands.

In relation to the physical interconnection, future networks should be highly reliable and provide support to multiple simultaneous failures of nodes, links or both. In order to guarantee such reliability levels it is required to increase the nodal degree of the network and the graph connectivity. The natural evolution is to move from the mentioned physical rings (degree 2) to degree 3 interconnections at backbone and distribution levels. Several of these types of organized networks have been proposed for future physical backbone interconnection in [6].

This work is focused on the use of degree 3 interconnection graphs for WDM transport networks. Degree 3 graphs can potentially support two simultaneous failures but in order to guarantee this they must be 3-connected. In addition, these graphs result in the shortest length 3-connected networks and, consequently, minimum costs deploying them. This affirmation is empirically proved in the case study.

The **main goal** is to identify the economical and cost vs. availability consequences of using degree 3 2- and 3-connected graphs to interconnect several set of nodes. The number of links in both types is the same but the different distribution of the links implies different characteristics. In order to obtain concrete numerical results, three scenarios are presented. These consist of a set of European, American, and Asian nodes to be interconnected.

The interconnection for each scenario is designed following an optimization process, using as an objective function the minimization of deployment costs.

The rest of the document is as follows: Section II summarizes some important concepts in relation to this work. Section III presents the methods followed in the analysis. Section IV illustrates the concepts by performing several experiments. Section V finalizes this work by discussing the main conclusions.

II. Background

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

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

Links disjointness: In this work all the links are physically disjoint from each other.

Minimum number of links: It is desirable to design network with the minimum number of links to fulfill the connectivity requirements in order to minimize the deployment costs. In Section IV this affirmation is empirically proved for the tested scenarios.

Minimum Length Routing:

Primary connections between pairs of nodes follow the shortest physical length path. This type of routing is convenient in order to minimize the capacity required to fulfill the traffic demands and, consequently, the deployed fiber. Minimum length routing is used instead of minimum hop count routing since long-haul WDM networks are circuit switched based. There is no packet processing time at the nodes delaying the transmissions, thus, the hop count is not as critical as for packet switched networks.

1+1(+1) Dedicated Protection: Protection is a failure support mechanism that consists of providing alternative paths when a failure is disrupting the primary one between a pair of nodes. 1+1 dedicated protection implies one alternative path for each primary path. Each alternative path is provided with 100% of the capacity to support the traffic when the primary path is unavailable. In a similar way, 1+1+1 is defined as the provisioning of 2 alternative paths for each primary, implying connectivity even if the primary and one of the alternative paths are unavailable.

Downtime, D: This parameter is used to statistically quantify, on average, the time the connectivity is lost between a pair of nodes per year. Hardware failure and cable cuts are the only reasons considered in this work to break a connection. Downtime is calculated based on availability A as $D = (1 - A) \cdot TimePeriod$.

III. METHODOLOGY

The methodology followed in the work to obtain results regarding the deployment cost and availability of the different interconnections is to solve the problem for several set of nodes and then calculate the relevant parameters. Each one of these interconnection problems belongs to the class NP [7] and [8] and, consequently, computationally heavy to solve. For practical reasons, these are by solved using heuristics in this work.

The interconnections designed in the different scenarios are the result of an optimization process. The objective function used in this process is minimum deployment cost, similar strategies can be found in [6].

In addition, specific routing and failure support schemes must be defined in order to be able to allocate the required capacity for each link and to calculate the availability numerical values. Minimum Length Routing and 1+1(+1) Dedicated Protection is used and applied to case studies.

A. Solution Search

As mentioned above, heuristics are used for solving this type of interconnection problems. However, depending on the kind of characteristics of the desired interconnection the methodology varies. Two different approaches are followed based on the input and output of the problem. In both cases the common input are the coordinates of the nodes and the traffic they aggregate to the network.

Topology Related Approach: This is followed when the interconnection is following a specific adjacency matrix. The input to the problem is a generic adjacency matrix describing the desired topology and the mentioned node information. The output of the problem is the position of each specific node in the adjacency matrix to optimize the objective function.

This method has been used in [6] and [9] to design the physical interconnection as organized topologies. In this work this approach is used for optimizing the interconnection as a ring topology.

Link Related Approach: This is followed when the adjacency matrix is unknown. A set of constraints is given as an input to the problem together with the nodes information. The output is the adjacency matrix and the position of each specific node in it to optimize the objective function.

This approach used in this paper has been introduced in [10] for optimizing 3-connected graphs.

Basically, this approach takes advantage of the solution generation procedure since it guarantees degree 3 graphs as offspring and therefore not incurring in unfeasible solution due to the degree constraint that might affect the efficiency of the method. Then, the connectivity constraint (2 or 3), must be evaluated for each new solution and the objective function determines if it is valid to maintain it in the process, or if it must be discarded.

B. Objective Function and assumptions

The objective function used in this problem to solve the interconnection problem is the *minimum deployment costs*. The deployment costs are calculated based on the model described in [6]. Basically, this model considers the costs for trenching, fiber spans, and switching nodes. Fiber spans include the costs of the optical fiber and the optical amplifiers.

All cost values are modeled relative to the cost of a single wavelength (denoted as $I_\lambda = 1$). In this way, the cost for trenching 1 km is $I_l = 1000$, of the termination equipment per fiber is $I_{lfix} = 50$, and cost per span is $I_{span} = 50$. The span distance is 80 km. For example, for a 160 km line with 3 fibers, the trenching cost is $160 \cdot 1000$ and the fiber cost is $3 \cdot 50 + 6 \cdot 50$, resulting in a total of 160450 units. All these values including switching costs can be found as in [6].

Usually, to minimize this cost implies a minimization of the networks length when trenching is required to place the fiber since it is significantly the most expensive task in deployment. Hence, for the result of any of these two minimizations should result in the same interconnection.

IV. CASE STUDY

This section describes the two experiments performed and the results are discussed. Both experiments consist of 3 scenarios with a set of 16 nodes each: European, American, and Asian backbone defined for this study.

The deployment costs and availability values are calculated following the models described in [6]. These are the specific parameters used for link dimensioning: 16 wavelengths per fiber, 40 Gbs per wavelength, and 1Mbs of aggregated peak traffic per user. The number of user is given randomly to each node; the exact values are presented in Appendix. Consequently the total traffic aggregated by each node is $users \cdot 1Mbs$.

A. Experiment A: 2-connected vs. 3-connected

This experiment consists of designing the interconnection for a set of nodes following the following topologies: Ring, degree 3 2-connected, and degree 3 3-connected. The Ring is the shortest 2-connected topology and it is used as a lower bound reference.

Downtime and capacity allocation are determined considering 2 disjoint paths (1+1 protection) in the Ring case. In the degree 3 2-connected, 3 disjoint paths (1+1+1 protection) are provided between pairs of nodes if possible; for the rest, 2 disjoint paths are used for the allocation. In the degree 3 3-connected case 3 disjoint paths are provided between each pair of nodes. Each of the optimizations was run several times and the minimum results were taken.

Table I presents the numerical results obtained for the three scenarios and the three topologies for each of them. These results are the total length of the network that is equivalent to the length of the required trenches, deployment costs in 10^5 cost units, and the average downtime in minutes per year.

EUROPE	Ring	Deg.3 2-con	Deg.3 3-con
Lenght (km)	8855	14857	15243
Trenching Cost	88.6	148.6	152.4
Span+Nodes Cost	1.8	1.4	1.7
Total Cost	90.4	150	154.1
Avg. Downtime (m/y)	2.7	1.5	0.003

AMERICA	Ring	Deg.3 2-con	Deg.3 3-con
Lenght (km)	11404	18477	20577
Trenching Cost	114	184.8	205.8
Fibre+Amps Cost	2.7	1.5	2.5
Total Cost	116.7	186.3	208.3
Avg. Downtime (m/y)	3.2	1.6	0.004

ASIA	Ring	Deg.3 2-con	Deg.3 3-con
Lenght (km)	21221	34895	35588
Trenching Cost	212.2	348.9	355.9
Fibre+Amps Cost	5.6	3.8	5
Total Cost	217.8	352.7	360.9
Avg. Downtime (m/y)	5.9	2.1	0.009

TABLE I
COST AND DOWNTIME RESULTS

The experiments present some consistency in the patterns of the results. Regarding the total length of the network, to deploy degree 3 graphs would imply 60-80% longer networks than the Ring. In connection to the connectivity of the degree 3 graphs, the 2-connected are always shorter than the 3-connected but the difference is not specially significant.

Regarding deployment costs, in all the cases the trenching cost corresponds to more than 90% of the total costs. This characteristic supports the affirmation that on these terms to minimize the deployment cost implies a minimization of the networks length.

In relation to the cost results of the fiber and optical amplifiers costs, the highest of these values corresponds to the ring due to the much longer paths between pairs of nodes. More fiber is required to allocate the required capacity. Regarding the 3-connected graph, these values are very similar but slightly lower than the ring. For the 2-connected graph option, the cost is significantly lower since it is not possible to provide and allocate capacity for 2 protection paths.

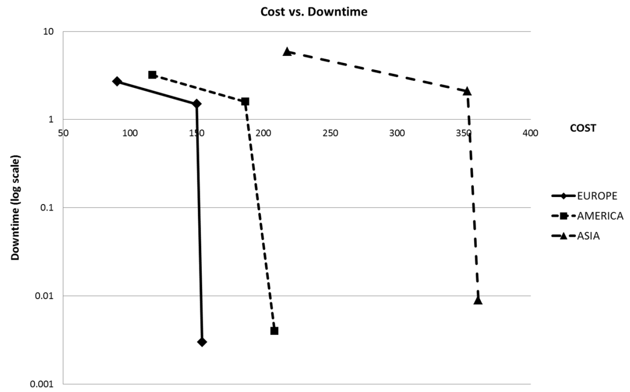


Fig. 1. Cost vs. Downtime

In connection with availability, the benefit of deploying a network allowing the third path implies a significant reduction on the average downtime. For the three scenarios, the downtime goes from minutes for the 2-connected option to milliseconds for the 3-connected graph.

Fig. 1 presents the comparison deployment cost vs. downtime in the three scenarios. The pattern followed in the three cases is constant and it can be noticed how the improvement from moving the degree 3 option from 2-connected to 3-connected is more significant than moving from the ring to the degree 3 2-connected. The slope of the lines between points can be interpreted as the availability benefit of increasing the deployment costs, the higher the better.

In summary, to deploy 3-connected graphs are slightly more costly (between 2-11% higher) than the 2-connected option but the improvement in availability pays of the extra investment by reducing the yearly downtime between 230-400 times.

Fig. 2 illustrates the resulting degree 3 3-connected graphs for the three scenarios.

B. Experiment B: 3-connected solution vs. Number of links L

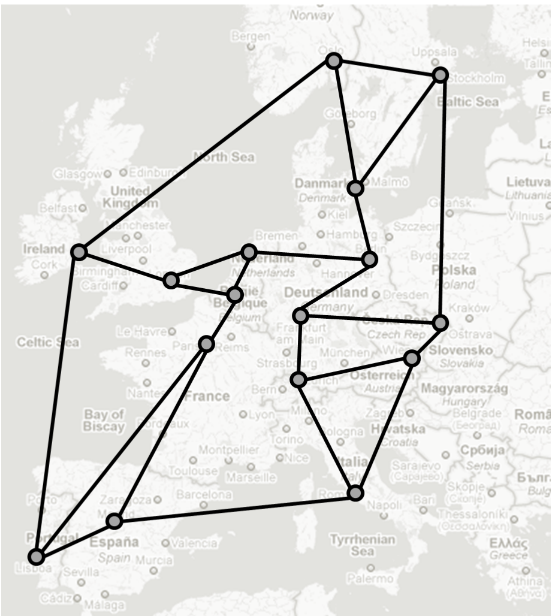
This experiment consists of designing 3-connected graphs using more than $3N/2$ links for the same three scenarios. The purpose is to verify that the minimum deployment cost for a 3-connected network corresponds to a degree 3 topology. The number of links is varied between 25 and 30.

Fig. 3 illustrates the total deployment cost results for this experiment. The values are normalized over results from the previous example of the 3-connected graphs using 24 links.

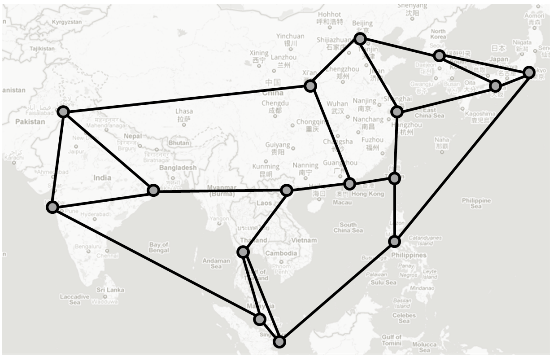
It can be concluded from these results that, as least for the scenarios covered, the minimum deployment cost corresponds to the graph with the least links, the degree 3. Moreover, the cost always increases with L.

V. CONCLUSION

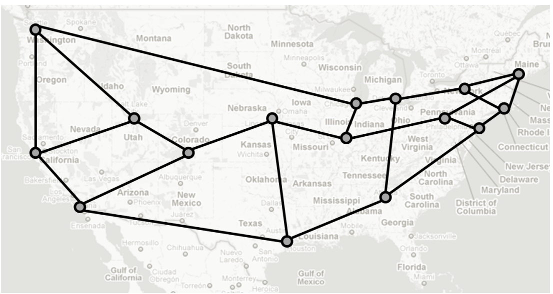
This work is focused on the analysis of degree 3 interconnection schemes for WDM transport networks. The analysis show the effect on the deployment costs and availability by the way links are distributed to physically interconnect nodes.



(a) Europe



(b) America



(c) Asia

Fig. 2. Degree 3 3-connected Solutions

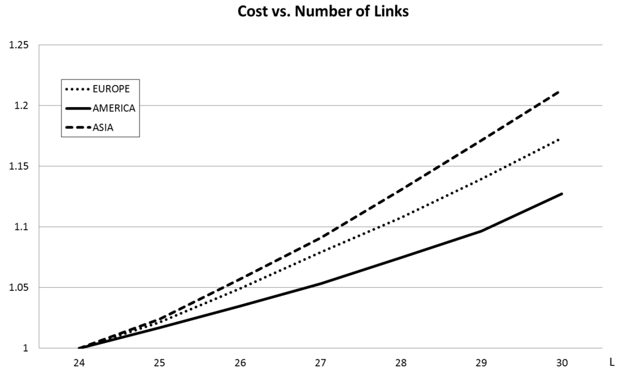


Fig. 3. Cost vs. Number of Links

This distribution is not a trivial problem since costs should be minimized without compromising the availability of the connections between pairs of nodes. Therefore, it is not enough to deploy a network increasing the nodal degree from 2 to 3, but also the resulting graphs should be 3-connected.

Based on the case study, to deploy 3-connected graphs implies higher costs since the resulting networks are always longer than the 2-connected solution. However, the improvement on the availability of the connections is very significant, the yearly downtime is reduced by factors of 230-400 depending on the case.

In terms of fiber and amplifiers costs, to deploy a 3-connected network should not imply higher costs than deploying a ring to interconnect the same set of nodes. All these affirmations always consider minimum deployment costs optimization.

In addition, the results from a second experiment show that degree 3 graphs are not only the interconnection with the fewest links to provide 3-connected networks, but also they imply the lowest deployment costs.

In summary, degree 3 3-connected physical interconnection schemes are an interesting option for future optical transport network. Their deployment costs are higher than for other options but if the lines are co-located with other network levels such as distribution or access network; the trenching cost could be shared.

Appendix

Nodes and Assigned Population:

EUROPE: London 363028, Amsterdam 357.823, Paris 591.856, Milan 511.144, Berlin 428.367, Prague 645.906, Rome 190.316, Madrid 893.309, Brussels 672.621, Oslo 439.882, Frankfurt 102.064, Dublin 953.677, Lisbon 996.562, Stockholm 165.973, Copenhagen 282.730, Vienna 720.069.

AMERICA: Cambridge 829.476, Seattle 375.432, Chicago 64.7296, Houston 355.200, San Diego 319.041, Atlanta 767.399, Pittsburgh 1.160.968, Salt Lake City 1.166.269, Boulder 989.938, Palo Alto 1.141.920, Ithaca 816.222, Ann Harbor 1.593.197, Princeton 1.334.658, Lincoln 439.575, Champaign 525.786, College PK 1.408.143.

ASIA: Kolcuta 817871, Beijing 841804, Tokio 1766961, Mumbai 1727558, Kuala Lumpur 1970649, Singapore 1495495, Hanoi 325161, Xian 1977383, Taipei 1113734, Bankok 1025479, Hong Kong 257088, Seoul 1701337, Lahore 554665, Shanhai 617598, Manila 959483, Osaka 348500.

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