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Increasing the cost-constrained availability of WDM Networks with Degree-3 Structured Topologies

Jose M. Gutierrez[1], **Kostas Katrinis**[2], **Kostas Georgakilas**[2], **Anna Tzanakaki**[2] **and Ole B. Madsen**[1]
[1] *Aalborg University, Networking and Security Section, Fredrik Bajers vej 7, 9220 Aalborg Ø, Denmark*
[2]*Athens Information Technology (AIT), 19.5 Markopoulou Av., P.O. Box 68, 19002 Peania, Greece*
Email: jgl@es.aau.dk

ABSTRACT

This paper studies the impact of node degree distribution to availability and capital and deployment expenditure of optical WDM transport networks. Three structured degree-3 graphs with fair node degree distribution are proposed in this context. Using a realistic network optimization framework based on genetic algorithms, we evaluate the performance of structured topologies and compare it against a practical topology (NSFNET). The results manifest that nodal degree fairness leads to increased availability compared to conventional topologies, while not incurring higher capital and deployment cost.

Keywords: Optical Network Planning, Topology Decision, Degree 3 networks, Genetic Algorithms

1. INTRODUCTION

The traffic supported by the Internet has grown enormously over the last few years shaping up the requirements that next generation networks need to support. This continuous increase of bandwidth requirements clearly indicates that optical network technology based on wavelength division multiplexing (WDM) will play a key role in support of these networks. As WDM optical networks can support enormous amounts of bandwidth over a single fibre, even single link failures may lead to loss of a huge volume of data. Therefore, future optical networks need to be designed to be fault tolerant to ensure high availability [1].

In this type of networks the topology planning and dimensioning problem is usually treated as a cost function optimization given a set of specific network requirements. The cost function can be, for example, number of Optical Cross-Connects (OXC's) [2], number of fibres/wavelengths [3], capital and deployment expenditure [4] or availability [5]. Part of the above optimization problems exhibits exponential complexity and thus heuristic methods e.g. Genetic Algorithms (GA) [2], Simulated Annealing (SA) [4] constitute in practice an efficient approach to derive near optimal solutions in relatively short time.

In the context of network resilience, the network topology per se can play a significant role when failures occur [6]. More specifically, structured network interconnection schemes have been shown to maintain full connectivity between nodes even in the occurrence of link/node failures due to their topological properties [7].

Preliminary work on the impact of a transport network's topological properties to cost-constrained availability has been presented in [8], focusing on regular topologies and using GAs for optimizing availability. However, the work in [8] did not specifically consider the cost aspects and network requirements of WDM networks. This paper extends the work presented in [8] by studying availability in WDM networks, considering also capital and deployment expenditure and comparing the performance and cost of regular topologies against real topologies (NSFNET). To the best of our knowledge the novel contributions of this work can be defined to be the development of a methodology that can be used to evaluate the performance of alternative WDM network topologies in terms of network availability and the associated capital and deployment expenditure. In this context, three distinct degree-3 structured i.e. Double Ring (DR), two Chordal Rings (CR) and the practical NSFNET topologies were examined and compared with respect to cost and availability. The evaluation results indicate that the DR and CR topologies provide the highest availability, but only the DR can offer this availability benefit without any additional capital and deployment cost compared to NSFNET.

The rest of this paper is structured as follows. Section 2 introduces definitions and assumptions, and outlines the planning framework used. Section 3 outlines the optimization method and presents the evaluation results. Finally, Section 4 presents the conclusions of the work.

2. NETWORK PLANNING FRAMEWORK

2.1 Definitions

Throughout this work, the term **disjoint** refers to node-disjointness (and thus also link-disjointness). It is assumed that all physical links of any of the topologies studied are physically independent, which implies that failures of distinct links occur independently. To distinguish between geographical distance and number of nodes traversed by a lightpath, we use the term **"distance"** to refer to the hop count of a path (denoted as $HP_n(x,y)$) and the term **"length"** to refer to physical distance covered by links ($l(i,j)$) or paths ($LP_n(x,y)$). **Euclidean distance** is considered for the links connecting cities.

Availability, [6] and [9] is the probability of a system to be in operating state at some point in time t in the future, given that the system started in operating state at time $t=0$. Random failures bring the system to the down state, at which the system remains for a random duration (**downtime**). It is also assumed that repair actions following a downtime period manage to always return the system to the operating state. The availability figures used in this paper account only for equipment failures; as such, connection unavailability due to mis-configuration or malicious interventions are not considered. For all availability results, we report average values; still, the method presented within this paper can be used without modifications to evaluate further statistical metrics of interest (e.g. minimum values).

2.2 Availability and Cost models

Table 1 and Eq. (1-6) define the availability and cost models employed in this paper. The availability values are taken from [9] and all cost values are modelled relative to the cost of a single wavelength (denoted as $I\_\lambda=1$).

Table 1. Variables description

Variable	Description	Value	Variable	Description	Value
N	Number of nodes	16	$A\_C\ (x,y)$	Avail. of connectivity between x-y	Eq. (3)
L	Number of links	24	I_trch	Trenching cost per km	1000
W	Number of λ per fibre	16	I_lfix	Term. equip. cost per fibre	50
CW	Wavelength bit rate	10 Gb/s	I_span	Fibre cost per span	50
$d_p(x,y)$	Hop distance of Path p between x- y	variable	$I\_sw(n)$	Switches price: 2x2/4x4/8x8/ 16x16/64x64/128x128	3/8/15/30/65 /150/350
$l(i,j)$	Link length $(i$-$j)$	variable	$I\_link(i,j)$	Total cost of the link $(i$-$j)$	Eq. (4)
l_{span}	Span length	80km	I_node_n	Cost of switching node n	Eq. (5)(a)
$n\_la\ (i,j)$	Line amps. link (i-j)	Eq. (1)(a)	I_NT	Total network cost	Eq. (5)(b)
A_l	Avail. per km of link	0.9999998	$TRF(x,y)$	Traffic volume (in Gbps) between nodes x and y	Eq. (6)(a)
A_la	Avail. of the line amps	0.9999996	$n\lambda(x,y)$	Num. of λ between x-y	Eq.(6)(b)
A_in	Avail. intermediate node	0.999957	$nf(i,j)$	Fibres between i and j	variable
A_tn	Avail. Tx/Rx node	0.9994241	$T\lambda\ (i,j)$	Transit λ between i and j	variable
$A\_link(i,j)$	Link Avail. $(i$-$j)$	Eq. (1)(b)	Pop_i, Pop_t	Population of i, Total pop.	- , 13870520
$A\_Path_p\ (x,y)$	Avail. of path p between x-y	Eq. (2)	$Userbw$	Traffic aggregated by user	1 Mbs

$$n\_la(i,j)=\lfloor l(i,j)/lspan \rfloor \text{ (a)} \qquad A\_link(i,j)=A\_l^{\,l(i,j)}\cdot A\_la^{\,n\_la(i,j)} \text{ (b)} \tag{1}$$

$$A\_Path_p\,(x,y)=A\_in^{d_n(x,y)-1}\cdot A\_tn^2\cdot\prod_{m=1}^{d_p(x,y)} A\_link_m \rightarrow A\_link_m\in A\_Path_p\,(x,y) \tag{2}$$

$$A\_C(x,y)=1-\prod_{p=1}^{k}(1-A\_Path_p\,(x,y))\rightarrow k=\text{disjoint paths} \tag{3}$$

$$I\_link(i,j)=I\_trch\cdot l(i,j)+2\cdot nf\cdot I\_lfix+nf(i,j)\cdot\left(\left\lfloor\frac{l(i,j)}{l_{span}}\right\rfloor+1\right)\cdot I\_span \tag{4}$$

$$I\_node_n=I\_sw(n)\cdot W \text{ (a)} \qquad I\_NT=\sum_{n=1}^{N}I\_node_n+\sum_{m=1}^{L}I\_link_m \text{ (b)} \tag{5}$$

2.3 Traffic Matrix and Routing

The input traffic matrix is generated based on the population assigned to each node. Two different population assignment techniques are used, namely a) randomly in the [100.000, 2.000.000] interval, used for the main experiments and b) proportionally to the degree of each node, using the NSFNET topology as a reference, only used in the Balanced-Population Trial. Subsequently, each source/destination pair is assigned a traffic demand that is proportional to the population of the source/destination nodes. Specifically, the (symmetric) traffic between nodes x and y is specified, similarly to [10], according to the following equations:

$$TRF(x,y)=\frac{Userbw\cdot Pop_x\cdot Pop_y}{Pop_t} \text{ (a)} \qquad n\lambda(x,y)=\left\lfloor\frac{TRF(x,y)}{CW}\right\rfloor+1 \text{ (b)} \tag{6}$$

The routing scheme used in this work is k-shortest paths using two well-established link weighting schemes: a) Hop-count (HC) routing, i.e. equally weighted links, whereby length-based routing is used for tie breaking and b) Minimum-Length (ML) routing, by tagging each physical link with the geographical distance it covers.

3. PLANNING APPROACH AND RESULTS

In this paper, we propose the use of degree-3 structured graphs for establishing physical connectivity of long-haul WDM networks. Three distinct structured topologies that were generated based on the placement of the 16 nodes of the NSFNET topology were examined i.e. a) Double Ring (DR), b) Chordal Ring (16,5) (CR) and c) Chordal Ring (16,7). All these topologies incorporate 24 links. More detailed information on these topologies can be found in [7]. The GA used as optimization method is a modification of the one presented in [8] with the additions of the routing scheme, input traffic and objective functions and presence of multiple wavelengths per link.

Following the implementation of the optimization method the availability and incurred cost associated with the proposed structured topologies as input were produced. In addition, the same set of results i.e. availability and cost were generated for the conventional NFSNET topology. For certain demands (2-degree nodes as source or destination), only 2 disjoint paths are assumed for the calculations.

Table 2 presents the results for two and three disjoint paths, after optimizing (alternately) against cost and availability taken for all four topologies. Specific to using two disjoint paths for each demand, the NSFNET topology, albeit resulting in the worst availability, managed to score one of the lowest total capital and deployment costs among all alternatives. Among the structured topologies, the DR topology performed similarly to the NSFNET topology in terms of both downtime and cost. For the rest two structured topologies, there is an improvement on the average downtime that however comes at considerably higher cost compared to NSFNET.

In the case of three disjoint paths, it becomes straightforward that the structured topologies provided significantly higher availability compared to NSFNET. This is mainly due to the fact that the links of the organized topologies are evenly distributed allowing the establishment of three disjoint paths regardless of the source and destination of a demand. This is in contrast to the NSFNET topology including four 2-degree nodes that make it impossible to find three disjoint paths for all source/destination pairs. We also observe that length-based routing provided higher availability at equal or higher cost, compared to hop-based routing, across all structured topologies under the same conditions.

Among all the three structured topologies we tested in all scenarios, the DR was the most competitive, since it yielded high availability at a capital and deployment cost that was comparable to the cost of the NSFNET topology. In an effort to investigate whether the cost-competitiveness of the DR topology compared to NSFNET was due to the latter being more sparse or due to a (randomly selected) traffic matrix that was in favour of DR, we conducted two further sets of optimization trials to compare DR with NSFNET under equal conditions with regard to node-degree (**Degree-Increment Trial**) and input traffic distribution (**Balanced-Population Trial**).

Since the unfeasibility of having three disjoint paths for some nodes clearly conditions the results for NSFNET, in the Degree-Increment trial we added two additional links (Chicago-Lincoln and Atlanta-Cambridge) to the initial NSFNET topology, resulting in a modified 26-links topology (MOD_NSFNET). To compare the two topologies under fair conditions, two links are also added to the DR configuration that yielded the least expensive solution (DR optimizing cost), forming MOD_DR. The decision of which two links to implement comes from a simple analysis of which combination of extra two short links (>1000km) offer the best availability. The optimization results in Table 3 (rows 1 and 2) show that the DR achieved higher availability at a lower cost. The cost of nodes and spans is presented to compare the cost values without the conditioning factor of trenching prices (approx. accounting for 95-99% of total cost).

The Balanced-Population aimed at lifting the randomness in population assignment that has been followed in the initial trials, which could have been of potential benefit for DR. The second population assignment is used here that *a priori* benefits the NSFNET topology. The total population Pop_t is distributed proportionally to each node's degree. Following this procedure, higher degree nodes will cover a large population. Again here, the results (Table 3, rows 3 and 4) manifest that the DR topology did not score worse against any of the two criteria compared to NSFNET.

Table 2. Two and Three disjoint paths results

Top.	**Routing**	**Optimization**	**2 Disjoint Paths**		**3 Disjoint Paths**	
			Cost	**Downtime, m/y**	**Cost**	**Downtime, m/y**
NFSNET	HC	None	24.301.142	1.872	24.540.282	0.859
	ML	None	24.297.502	1.844	24.540.182	0.848
DR	HC	Cost	24.226.411	1.853	24.721.471	0.00502
		Avail.	24.226.411	1.853	26.122.993	0.00490
	ML	Cost	24.222.871	1.828	24.715.671	0.00500
		Avail.	25.672.133	1.818	26.139.493	0.00493
CR(16:5)	HC	Cost	29.382.401	1.803	29.789.421	0.00453
		Avail.	29.627.846	1.791	30.013.006	0.00449

	ML	Cost	29.378.661	1.785	29.792.321	0.00454
		Avail.	29.617.126	1.760	30.033.306	0.00451
CR(16:7)	HC	Cost	25.775.367	1.879	26.257.388	0.00499
		Avail.	26.593.057	1.835	27.134.961	0.00479
	ML	Cost	25.774.767	1.872	26.252.787	0.00500
		Avail.	27.071.516	1.800	26.655.196	0.00476

Table 3. Sensitivity results (Degree Increment and Balanced Population)

Topology	Routing	Variation	Cost	Downtime(min/y)	Nodes+Spans Cost
MOD_NSFNET	HC	Degree increment	26.906.862	0.00433	772.540
	ML		26.903.862	0.00430	769.540
MOD_DR	HC		26.286.675	0.00422	749.500
	ML		26.287.575	0.00422	749.400
NSFNET_BAL (2 paths)	HC	Balanced population	24.323.582	1.872	457.460
	ML		24.323.822	1.844	457.700
DR_BAL (2 paths)	HC		24.253.851	1.853	458.880
	ML		24.246.291	1.828	451.320

4. CONCLUSION

This paper addressed the efficacy of structured topologies in the context of optical WDM transport networks. Within a realistic flow-allocation and equipment/trenching cost framework, we implemented a Genetic Algorithm heuristic that has been used as an efficient solution-search method to compute feasible, near-optimal network designs, given an initial topology and an input traffic matrix. Using this experimental setting, we evaluated three distinct degree-3 structured topologies against cost and availability (alternately). As a realistic benchmark, we also evaluated the conventional NSFNET topology, using the same setting.

The evaluation results manifest that the DR and CR topologies provide the highest availability, but only the DR can offer this availability benefit without any additional capital and deployment cost compared to NSFNET. This superiority was marginal compared to NSFNET for the case of requiring two disjoint paths among all source/destination pairs, while it was significant in the case of three disjoint paths. This can prove to be extremely cost-efficient in the case, where the availability requirements of a network become important. While in such a situation the NSFNET topology would need to grow to reach higher availability levels, a Double Ring topology could serve these needs without applying upgrades to it, and in fact at a slightly lower cost. Last, we note that this finding was insensitive to the minimum node-degree of the NSFNET topology, as well as to the randomness of the input traffic demands.

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