Evaluation and Design of Elastic Optical Networks Resilient to Multiple Node Failures

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Presentation Outline

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Work Contextualization

Consider an existing **Elastic Optical Network** (EON) with a given topology composed by **nodes** and **connecting fibers**, each fiber with a given **spectrum capacity**.

Consider an estimated set of **demands** to be supported and a **Routing, Modulation and Spectrum Assignment** (RMSA) policy adopted by the operator.

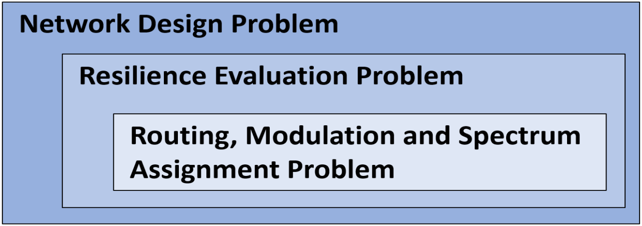
Main goals:

- Assess the multiple node failures resilience of existing EON topologies.
- Address the design problem aiming to determine a new EON maximizing the resilience metric imposed by its critical nodes.

Problem Description

The proposed EON problem is a **max-min-max tri-level** optimization problem:

- Compute an EON **maximizing** its evaluation value.
- The set of node failures aims to **minimize** the demand percentage that the RMSA policy is able to support.
- RMSA policy aims to **maximize** the demand percentage that is supported (by a given set of node failures).



Network Design Problem

Resilience Evaluation Problem

Routing, Modulation and Spectrum Assignment Problem

Routing, Modulation and Spectrum Assignment

The **RMSA policy** rules the way lightpaths are assigned both in the regular state and in any failure state.

Consider the EON topology represented by an **undirected graph** $G = (N, E)$:

- $N = \{1, ..., |N|\}$ – set of nodes;
- $E \subseteq \{(i, j) \in N \times N : \; i < j\}$ – set of links;
- $l_{ij} > 0$ – length of link $(i, j) \in E$ (in km).

$F = \{1, ..., |F|\}$ – ordered set of **frequency slots** (FSs).

D – set of **demands** (single line rate optical network). Each $d \in D$ is defined by its source and target nodes (s_d, t_d).

Routing, Modulation and Spectrum Assignment

M – set of **modulation formats**. Each $m \in M$ is defined by:

- n_m – number of required contiguous FSs;
- T_m – transparent reach (in km).

P_d – set of lightpath **candidate paths** to demand $d \in D$. Each $p \in P_d$ is defined by:

- $\alpha_{ij}^p \in \{0,1\}$ – indicating whether link (i,j) is in p or not;
- $\beta_k^p \in \{0,1\}$ – indicating whether node k is in p or not;
- $n_p \in \mathbb{N}$ – number of FSs required to allocate lightpath.

Optical length of p: $$\sum_{k=1}^{n-1} \sum_{t=k+1}^{n} \alpha_{kt}^p l_{kt} + \Delta\Big(\sum_{k=1}^{n} \beta_k^p - 2\Big)$$

Routing, Modulation and Spectrum Assignment

In this work, we consider that the **required number of FSs n_p depends on the candidate path** $p \in P_d$.

Moreover, for each $d \in D$, consider $n_d = \min_{p \in P_d} \{n_p\}$.

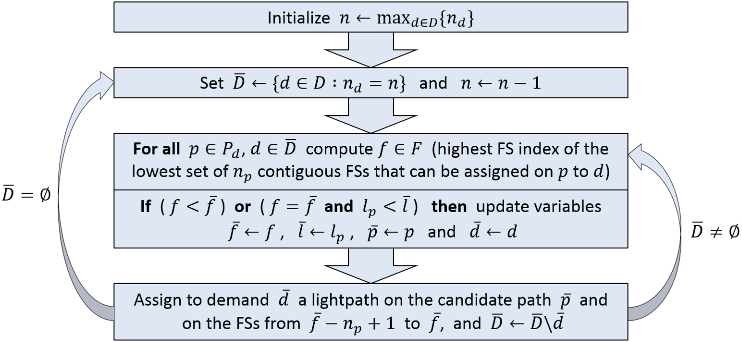
P_e – set of all candidate paths that include link $e \in E$.

$c_e = \sum_{d \in D} \sum_{p \in (P_d \cap P_e)} n_p$ – **collision metric** of link $e \in E$

$l_p = \sum_{e \in P} c_e$ – length of path $p \in \cup_{d \in D} P_d$ (according to this collision metric).

Routing, Modulation and Spectrum Assignment

RMSA policy (for the regular state):



Initialize $n \leftarrow \max_{d \in D}\{n_d\}$

Set $\overline{D} \leftarrow \{d \in D : n_d = n\}$ and $n \leftarrow n - 1$

For all $p \in P_d, d \in \overline{D}$ compute $f \in F$ (highest FS index of the lowest set of n_p contiguous FSs that can be assigned on p to d)

If $(f < \bar{f})$ **or** $(f = \bar{f}$ **and** $l_p < \bar{l})$ **then** update variables $\bar{f} \leftarrow f$, $\bar{l} \leftarrow l_p$, $\bar{p} \leftarrow p$ and $\bar{d} \leftarrow d$

Assign to demand $\bar{d}$ a lightpath on the candidate path $\bar{p}$ and on the FSs from $\bar{f} - n_p + 1$ to $\bar{f}$, and $\overline{D} \leftarrow \overline{D} \backslash \bar{d}$

$\overline{D} = \emptyset$

$\overline{D} \neq \emptyset$

Routing, Modulation and Spectrum Assignment

RMSA policy for the failure state is slightly different.

Lightpaths **not disrupted** by any failure node are **not changed**, *i.e.* we consider the surviving network with the FSs occupied by the non disrupted lightpaths.

For the disrupted demands whose end nodes are in the same component, a new set of candidate paths is computed.

Then, the RMSA is similar to the regular state but the demands are processed in **increasing order** of their n_d values (lightpaths requiring less number of FSs can better fit in the initial fragmented spectrum).

Resilience Evaluation problem

The EON resilience to multiple node failures measures their impact in the network capacity to support the demands.

For a given number $c \in \mathbb{N}$ of failure nodes, we adopt a **worst-case** approach by identifying a set of c critical nodes whose simultaneous failure **maximally reduce the demand percentage** that is supported.

We solve the problem heuristically by computing 2 sets of failure nodes, running the RMSA policy for each set and **selecting the most damaging set** as the critical node set.

1. Critical Node Detection (CND) problem;
2. *Node Demand Centrality* (NDC) method.

Critical Node Detection (CND) problem

For each node pair (i, j) consider a **weight** w_{ij} given by the sum of all demands $d \in D$ whose end-nodes are i and j.

Decision variables for optimization model:

- For each node $i \in N$,

$$v_i = \begin{cases} 1, \text{ if } i \text{ is a critical node;} \\ 0, \text{ otherwise.} \end{cases}$$

- For each node pair $i, j \in N : i < j$,

$$u_{ij} = \begin{cases} 1, \text{ if } i \text{ and } j \text{ are connected (through a path);} \\ 0, \text{ otherwise.} \end{cases}$$

Critical Node Detection (CND) problem

Integer Linear Programming (ILP) compact model for CND problem:

$$min \quad \sum_{i,j\in N: i<j} w_{ij}u_{ij} \tag{1}$$

$$s.t. \quad \sum_{i=1}^{n} v_i \leq c, \tag{2}$$

$$u_{ij} + v_i + v_j \geq 1, \qquad (i,j) \in E, \tag{3}$$

$$u_{ij} \geq u_{ik} + u_{jk} - 1 + v_k, \quad (i,j) \notin E,\ k \in N_{ij}, \tag{4}$$

$$v_i \in \{0,1\}, \qquad i \in N, \tag{5}$$

$$u_{ij} \in \{0,1\}, \qquad i,j \in N : i < j. \tag{6}$$

Node Demand Centrality (NDC) method

The proposed demand based centrality of each node $k \in N$ aims to **measure the impact** of the node failure on the demands between **all other node pairs**.

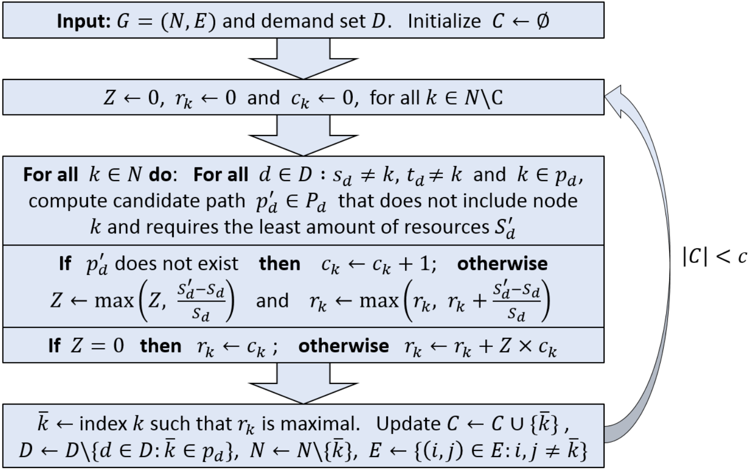
p_d – lightpath $p \in P_d$ assigned to demand $d \in D$.

The **resources used** by each lightpath p_d, denoted as S_d, are given by its number of FSs times the number of hops of its routing path, *i.e.* $S_d = n_d \times \sum_{(i,j)\in E} \alpha_{ij}^{p}$.

The **node failure impact** is measured as a combination of two quantities:

1. total demand that can no longer be supported;
2. minimum resources increase required to reassign new lightpaths to demands that can be connected.

Node Demand Centrality (NDC) method



Input: $G = (N, E)$ and demand set D. Initialize $C \leftarrow \emptyset$

$Z \leftarrow 0,\ r_k \leftarrow 0$ and $c_k \leftarrow 0$, for all $k \in N \backslash C$

For all $k \in N$ **do**: **For all** $d \in D : s_d \neq k, t_d \neq k$ and $k \in p_d$, compute candidate path $p'_d \in P_d$ that does not include node k and requires the least amount of resources S'_d

If p'_d does not exist **then** $c_k \leftarrow c_k + 1$; **otherwise** $Z \leftarrow \max\left(Z, \frac{S'_d - S_d}{S_d}\right)$ and $r_k \leftarrow \max\left(r_k, r_k + \frac{S'_d - S_d}{S_d}\right)$

If $Z = 0$ **then** $r_k \leftarrow c_k$; **otherwise** $r_k \leftarrow r_k + Z \times c_k$

$\bar{k} \leftarrow$ index k such that r_k is maximal. Update $C \leftarrow C \cup \{\bar{k}\}$, $D \leftarrow D \backslash \{d \in D : \bar{k} \in p_d\}$, $N \leftarrow N \backslash \{\bar{k}\}$, $E \leftarrow \{(i, j) \in E : i, j \neq \bar{k}\}$

Network Design problem

Rationale: Start with graph $G = (N, E_0)$ and randomly select one link at a time until no new link can be added within the given budget B (km).

Set of links E_0 – **Relative Neighbourhood Graph** (RNG): $i, j \in N$ are connected by a link if and only if there is no other node $k \in N \backslash \{i, j\}$ such that $l_{ik} \leq l_{ij}$ and $l_{jk} \leq l_{ij}$.

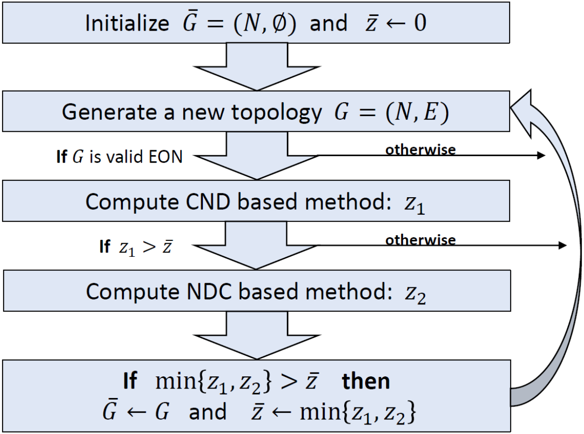
Define the probability $\mathbf{P}\big((i,j)\big)$ of each new link (i, j):

$$\mathbf{P}\big((i,j)\big) = \frac{1}{\left(|\delta_i - \delta_j| + 1\right)\ {l_{ij}}^2} \tag{7}$$

for all node pairs $(i, j) \notin E$ such that $l_{ij} \leq B_R$ and at least one end-node has minimum node degree.

Network Design problem

Multi-Start Greedy Randomized algorithm:



Initialize $\bar{G} = (N, \emptyset)$ and $\bar{z} \leftarrow 0$

Generate a new topology $G = (N, E)$

If G is valid EON — **otherwise**

Compute CND based method: z_1

If $z_1 > \bar{z}$ — **otherwise**

Compute NDC based method: z_2

If $\min\{z_1, z_2\} > \bar{z}$ **then**
$\bar{G} \leftarrow G$ and $\bar{z} \leftarrow \min\{z_1, z_2\}$

Computational Results

Parameters:

- $|F| = 320$ FSs; $c \in \{2, 3, 4, 5, 6\}$; $\Delta = 60$;
- For all $d \in D$, $|P_d| = \min\{7,\ \sum_{k=1}^{n} \beta_k^p + 1\}$, where p is the shortest path between nodes s_d and t_d.
- Modulation format configurations:

m	n_m	T_m (km)
1	1	500
2	2	1250
3	3	2000
4	4	2500

Computational Results

Topology characteristics of each tested network:

Network	$\|N\|$	$\|E\|$	Pairs	$\bar{\delta}$	2-C	L	Diameter
Germany50	50	88	1225	3.52	Yes	8859	1417
PalmettoNet	45	64	990	2.84	No	4286	1298
MissouriNA	64	80	2016	2.50	No	4001	1301

Regarding the set of demands D, we consider:

- 4 sets for Germany50, with increasing number of demands (Ger_a, Ger_b, Ger_c, Ger_d);
- 2 sets for both PalmettoNet (Pal_a, Pal_b) and MissouriNA (Mis_a, Mis_b).

Resilience evaluation of existing networks

Instance	RMSA t(s)	c	CND method		NDC method	
			Value	t(s)	Value	t(s)
Ger_a	23	2	0.8433	2	**0.8283**	12
		3	**0.5750**	1	**0.5750**	4
		4	**0.5200**	2	**0.5200**	4
		5	**0.4050**	3	0.4983	5
		6	**0.3350**	3	0.4683	9
Ger_b	50	2	0.8457	4	**0.7380**	22
		3	**0.5804**	2	**0.5804**	5
		4	**0.5224**	3	**0.5224**	6
		5	**0.4049**	5	0.5004	7
		6	**0.3388**	6	0.4727	13
Ger_c	51	2	0.8257	3	**0.7236**	23
		3	**0.5878**	2	**0.5878**	5
		4	**0.5345**	3	**0.5345**	6
		5	**0.4128**	4	0.5088	12
		6	**0.3453**	5	0.4149	8
Ger_d	52	2	0.8128	3	**0.7119**	23
		3	**0.5930**	2	**0.5930**	5
		4	**0.5252**	7	0.5426	6
		5	**0.4186**	5	0.5084	12
		6	**0.3357**	4	0.4284	9

Resilience evaluation of existing networks

Instance	RMSA t(s)	c	CND method Value	CND method t(s)	NDC method Value	NDC method t(s)
Pal_a	19	2	**0.5165**	1	0.5496	2
		3	**0.3430**	1	0.4587	3
		4	**0.2769**	1	0.2851	3
		5	**0.1653**	1	0.2190	3
		6	**0.1116**	1	0.1632	4
Pal_b	24	2	**0.5161**	1	0.5528	2
		3	**0.3492**	1	0.4594	3
		4	**0.2833**	1	0.2925	3
		5	**0.1730**	1	0.2266	4
		6	**0.1194**	1	0.1715	4
Mis_a	51	2	**0.4657**	2	0.8770	8
		3	**0.2964**	2	0.6694	17
		4	**0.2218**	2	0.3327	11
		5	**0.1593**	2	0.2581	12
		6	**0.1169**	2	0.1734	12
Mis_b	69	2	**0.4598**	3	0.8720	9
		3	**0.3140**	3	0.6592	18
		4	**0.2366**	3	0.4271	12
		5	**0.1652**	3	0.2470	11
		6	**0.1265**	3	0.1786	12

Network Design - Generation and Validation

Instance	Valid	Time (hh:mm:ss)		
	EONs	Generation	Topology Val.	RMSA Val.
Ger_a	929	00:00:01	00:00:48	06:52:47
Ger_b	676	00:00:01	00:00:47	14:02:58
Ger_c	260	00:00:01	00:00:46	14:09:54
Ger_d	23	00:00:01	00:00:46	14:20:49
Pal_a	1000	00:00:01	00:00:01	04:52:14
Pal_b	999	00:00:01	00:00:01	07:10:13
Mis_a	1000	00:00:01	00:00:01	12:16:21
Mis_b	1000	00:00:01	00:00:01	18:41:03

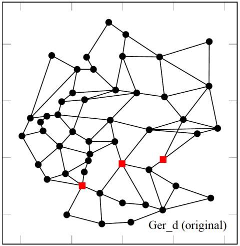
Network Design - Evaluation

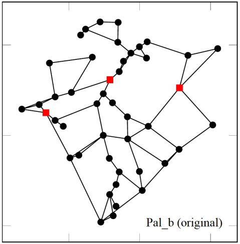
Instance	c	Original	Best	Time (hh:mm:ss)
Ger_a	2	0.8283	0.9200	00:51:53
	3	0.5750	0.8067	00:51:07
	4	0.5200	0.6517	00:51:14
	5	0.4050	0.5150	00:48:57
	6	0.3350	0.4217	00:45:04
Ger_b	2	0.7380	0.8824	01:17:15
	3	0.5804	0.7624	01:17:22
	4	0.5224	0.6490	01:14:25
	5	0.4049	0.5224	01:11:58
	6	0.3388	0.4171	01:01:32
Ger_c	2	0.7236	0.8588	00:27:55
	3	0.5878	0.7500	00:31:41
	4	0.5345	0.6466	00:32:11
	5	0.4128	0.5162	00:30:02
	6	0.3453	0.4135	00:25:48
Ger_d	2	0.7119	0.8191	00:04:18
	3	0.5930	0.7246	00:03:47
	4	0.5252	0.6214	00:05:32
	5	0.4186	0.5142	00:04:04
	6	0.3357	0.3878	00:03:23

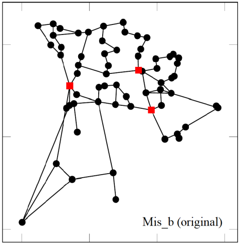
Network Design - Evaluation

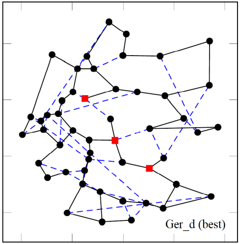
Instance	c	Original	Best	Time (hh:mm:ss)
Pal_a	2	0.5165	0.8306	00:30:37
	3	0.3430	0.6488	00:28:59
	4	0.2769	0.4855	00:27:55
	5	0.1653	0.3533	00:22:56
	6	0.1116	0.2438	00:19:50
Pal_b	2	0.5161	0.8300	00:37:15
	3	0.3492	0.6493	00:33:26
	4	0.2833	0.4855	00:32:44
	5	0.1730	0.3553	00:26:36
	6	0.1194	0.2466	00:22:32
Mis_a	2	0.4657	0.8226	01:10:41
	3	0.2964	0.6935	01:40:11
	4	0.2218	0.5242	01:06:44
	5	0.1593	0.3992	01:05:17
	6	0.1169	0.3105	01:00:55
Mis_b	2	0.4598	0.8229	01:29:37
	3	0.3140	0.6979	02:03:13
	4	0.2366	0.5298	01:17:20
	5	0.1652	0.4033	01:17:49
	6	0.1265	0.3170	01:13:04

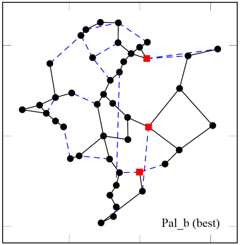
Original topologies and Best topologies

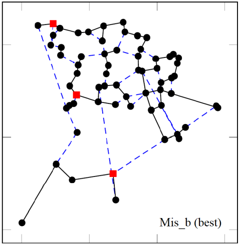




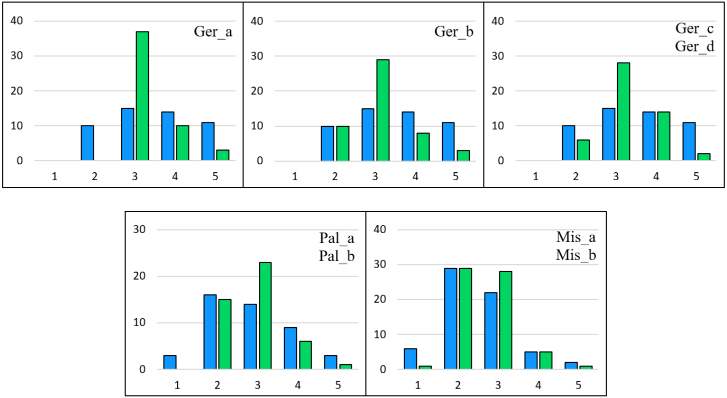








Node degree histograms



Remarks / Conclusions

- In this work, we have considered the evaluation and network design of EONs resilient to multiple node failures.
- First, we have addressed the resilience of EONs to multiple node failures by identifying the critical nodes whose simultaneous failure maximally reduce the demand percentage that is supported by the network.
- Second, we have addressed the design of a new EON maximizing the resilience metric imposed by its critical nodes.
- The results showed that EONs resilient to multiple node failures have topologies with more homogeneous node degrees which are very different from the original ones.

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RECODIS
Resilient communication services
protecting end-user applications
from disaster-based failures