

**International Conference – 2025: Developed India @ 2047****Charting Multidisciplinary and Multi-Institutional Pathways for Inclusive Growth and Global Leadership held on 4th & 5th April, 2025****Organised by: IQAC - Gossner College, Ranchi****Integer Linear Programming Model for Joint Optimization of Routing Spectrum Allocation and Regenerator Placement in Survivable Translucent Elastic Optical Networks****Shibsankar Bala ¹, Urmila Bala ¹, Dinesh Prasad ²**¹ Department of CSE, Asansol Engineering College, Asansol, West Bengal, India.² Department of Mathematics, Gossner College, Ranchi, Jharkhand, India.**ABSTRACT**

In Translucent Elastic Optical Networks (T-EONs), when optical signal is propagated beyond its transparent reach, it requires the signal regenerate via 3R-regeneration (re- amplification, re-timing and reshaping) for quality of transmission (QoT). 3R-regenerations are placed at some specific node (known as regenerator) in the network for regenerate the signal to maintain QoT and it takes the initial cost known as capital expenditure (CAPEX). Routing spectrum allocation (RSA) is the fundamental problem in any Elastic Optical Networks (EONs) by which it finds the route of the connection request and allocate the requisite number of spectrums to establish the connection. Another important cost is spectrum allocation for each connection request. Link failure or fiber cut is one of the important issues for any connection request in T-EONs because of huge traffic loss. So, survivability is an important issue to avoid traffic loss. In the existing literatures, so far no one has addressed the joint optimization of regenerator placement and spectrum allocation in survivable T-EONs. So, we proposed a novel Integer Linear Programming (ILP) model that optimizes jointly the CAPEX cost of the regenerators as well as the total number of allocated spectrums over the entire connection request in survivable T-EONs. The ILP model is run over IBM ILOG CPLEX version 12.8 on well known benchmark networks (NSF, US and COST-239) and gets the result.

1. Introduction

Elastic optical networks (EONs) are the backbone technology that plays a significant role in handling a huge amount of data that grown out of the massive growth of network users. The available bandwidth in optical fibers can be more efficiently utilized because of its flexibility.

The spectrum efficiency in EONs is provided by dividing the available bandwidth into thinner spectrum slices (12.5GHz) known as frequency slots (FS) [1]. As Orthogonal Frequency Division Multiplexing (OFDM) is used in EONs, the data transmission of optical signal is allowed to use various modulation formats (MFs) [1] for spectrum efficiency. The widely used MFs are Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 8- Quadrature Amplitude Modulation (8-QAM) and 16-QAM. Due to physical layer impairments and noise the quality of transmission (QoT) leads to degrade [2]. Thus, the signal transmitted using any MF has a maximum

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permissible optical reach called transparent reach (TR), a limiting distance within which the desired QoT can be maintained [2], [3]. In Table-1, it has been shown the various MFs and their corresponding TR with spectrum efficiency of data rate. In order to maintain the QoT, signal must go through under 3R-regeneration (re-shaping, re-timing and re-amplification) [4], [5]. This 3R-regeneration is carried out by considering some nodes as regenerator site from where the optical signal regenerates the quality to maintain QoT. Regeneration of the signal means, it undergoes Optical-Electrical-Optical (O-E-O) conversion [2], [3] at the regeneration site. In EONs, if some nodes are considered as regenerator site then it is called Translucent EONs (T-EONs). So the challenge is how to design the T-EONs so that the capital expenditure (CAPEX) to regenerate the signal by the regeneration node will be minimum. This problem is also called Regenerator Placement (RP) problem. In any network, the commonly occurring failure is a link failure (fiber-cut). Once the link failure is occurs that lead huge traffic disruption. So, survivability of EONs to protect a link is an important issue to address. To overcome this problem, we address survivability on translucent EONs is known as survivable translucent elastic optical networks (ST-EONs). Different protection techniques like Dedicated Path Protection (DPP) [6], Shared Path Protection (SPP) [7], Multi-Path based Protection (MPP) schemes [8] already have been developed.

Though the problem of regenerator placement (RP) [9-12] has been extensively addressed for T-EONs, few research has been done to address RP for survivable T-EONs (ST-EONs) but till now no one has jointly address routing and spectrum allocation (RSA) [13] along with minimum number of regenerators in ST-EONs. In this paper, we address the problem to minimize total number of used spectrums and number of regenerators jointly in ST-EONs under static scenario. We formulate an RSA-RP integer linear programming (ILP) to solve the above problem for designing ST-EONs in static scenario (offline).

The rest of the paper is organized as follows. In sec 2, the review of existing works in T-EONs and ST-EONs is included. In sec 3, an example to illustrate optimal RSA-RP in ST-EONs is provided. In sec.4, the proposed ILP formulation model is included. Performance comparisons are included in sec 5 and finally the concluding remarks are provided in sec 6.

2. Review Work

Translucent optical networks design concept was introduce by the author in [4]. The authors [9], proposed a branch-and-price algorithm to solve the RP problem for T-EONs. An ILP formulation for joint optimization of RP and spectrum utilization is presented in [10]. The work [11] proposed a scheme for RP that can reduce spectrum requirements in T-EONs. In [12], authors' focuses on the problem of RP in cloud-ready Elastic Optical Networks (EONs) that shown cloud-aware location of regenerators can significantly reduce the blocking probability as well as reduce the number of used regenerators.



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In [3] authors proposes the design of energy and spectrum efficient, multipath survivable Routing and Spectrum Allocation (RSA) scheme for regenerator aware ST-EONs. In [14], they proposed integrated approach for designing survivable EONs based on multipath protection to minimize energy consumption and spectrum requirement using Genetic Algorithm (GA). Authors of [15] proposed algorithms employ failure independent path protecting p-cycle (FIPP) in EONs. Also, they formulated an ILP and compare the results with the heuristic. In [16], authors proposed a RSA algorithm for T-EONs, and also design p-cycle algorithms for both static and dynamic traffic scenario. In [17], they demanded this is the first paper to address the problem of online dimensioning and survivability of OFDM based transparent optical grids. In [18] authors address the offline problem of Survivable Routing, Modulation and Spectrum Allocation in EONs using SPP.

3. Joint Optimal RSA-RP in ST-EONs

We consider an example to illustrate joint optimal RSA-RP in ST-EONs. The TRs of optical signal for different MFs are given in Table.1 [3]. When signal propagated beyond 4000 kilometers (km) (TR of BPSK), will require 3R-regeneration to regenerate the signal for QoT. An optical path segment from a node (source / regenerator) to other node (regenerator / destination) without going through any regenerator is known as transparent segment. In Fig.1, we consider a 7-node and 10-edges network with the edge length given in Kms. For this network, nodes 2, 4, 6 and 7 are considered as regeneration node so that every pair of connection request can establish a primary path and a link disjoint backup path using either a transparent segment or a set of transparent segments.

For example, In Fig.1 consider a connection request between node pair (1,3) with demand 100Gbps. This request can be established using the primary path $1 \rightarrow 2 \rightarrow 3$. Since the length of this path is 4000 Kms, BPSK will be used as the MF, no regeneration will be required and so a transparent segment has been established between node 1 and 3. To ensure survivability, this primary path will be protected by the link disjoint shortest backup path $1 \rightarrow 6 \rightarrow 4 \rightarrow 3$ whose distance (3000+1500+2000) is 6500 Kms. Since the backup path length is beyond 4000 kms, it requires regeneration at either node 6 or both the nodes (6 & 4) and then only a set of transparent segments will be established.

The possible cases for selecting regeneration node are (i) node 4 and 6 both ii) only 6. For case (i), transparent segments are $1 \rightarrow 6$ (3000 Kms), $6 \rightarrow 4$ (1500 Kms), and $4 \rightarrow 3$ (2000 Kms) may use BPSK for $1 \rightarrow 6$ and QPSK for $6 \rightarrow 4$ & $4 \rightarrow 3$. Whereas for case (ii) transparent segments are $1 \rightarrow 6$ (3000 Kms) and $6 \rightarrow 4 \rightarrow 3$ (3500 Kms) both use the modulation format BPSK. In case (i) total 16 FS are required and in case (ii) total 24 FS are required. So, case (i) is optimal. The calculation of FS corresponding to each path segment has been computed using the formula given in [18].



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Table: 1

Modulation format (MF)	Transparent reach (km)	# FS for 100Gbps
BPSK	4000	8
QPSK	2000	4
8-QAM	1000	3
16-QAM	500	2

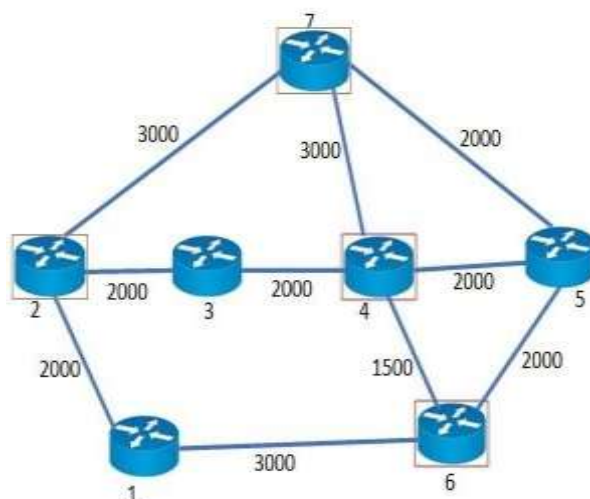


Fig: 1 7-node ST-EON with nodes numbered 2, 4, 6 and 7 identified as RP to ensure survivability.

4. Integer Linear Programming (ILP) Formulation for RSA-RP joint Optimization Model

This section presents an integer linear program (ILP) to solve the routing spectrum allocation and regenerator placement jointly (RSA-RP) in survivable translucent elastic optical networks (ST-EONs). Following notations and descriptions are required to represent the ILP. Let $G(V, E)$ be a directed graph representing an ST-EONs with node set V , and optical edge set E . The edge length is denoted by L_{ij} for each edge $(i, j) \in E$. Let M be the set of available modulation formats, where L_m denotes the maximum transmission reach corresponding to the modulation $m \in M$. Consider D as the set of demands. For each demand $d \in D$, we denote s^d as the source node, t^d as the destination node, and b^d as the requested bit-rate in Gbps.


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Table: 2

V	Set of nodes in ST-EONs
E	Set of edges in ST-EONs
M	Set of modulation formats
D	Set of demands
P	Set of feasible primary path segments
B	Set of feasible backup path segments
F	Set of frequency slots
C	Set of all available connections
$C(m, b_r)$	Subset of connections available for modulation m and bitrate b_r
s^d	Source node of demand $d \in D$
t^d	Destination node of demand $d \in D$
b^d	Bitrate requested by demand $d \in D$
s_p	Source node of path-segment $p \in P$
t_p	Destination node of path-segment $p \in P$
m_p	Modulation format associated with the path-segment p
$\eta_{i,j,p}$	Equal to 1 if arc $(i, j) \in E$ is part of the path-segment p .

We use the path segments formulation [9] for the route assignment of each connection request for their primary and backup path. A path segment p is a directed simple path with an associated modulation level m_p . We can calculate the length of the path segment p denoted by $l_p = \sum_{(i,j) \in E} L_{ij} * \eta_{i,j,p}$ as the sum of the links contained within p . Compute the length of all the path

segments corresponding to primary and backup path for each connection request using above computation. A path segment is feasible if its length within the transparent reach of the corresponding modulation format (Table-1). Assume that P and B are the set of all feasible primary and backup path segments respectively. Then a primary route of demand d is an ordered union of feasible path segments



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$p_v^i \in P, i=1, 2, \dots, k$; such that $t_{p^i} = s_{p^{i+1}}$ for all $i=1, 2, 3, \dots, k-1$ and $s^d = s_{p^k}$ along with $t^d = t_{p^k}$. Similarly, a backup route of demand d is also an ordered union of feasible path segments $p_v^i \in B, i=1, 2, \dots, b$; such that $t_{p^i} = s_{p^{i+1}}$ for all $i=1, 2, 3, \dots, b-1$ and $s^d = s_{p^b}$ along with $t^d = t_{p^b}$.

The requisite number of frequency slots (FS) a demand d depends on the modulation format used and the requested amount of bit-rate (b^d). So, we denote the set of connections $C(m, b_r) = \{1, 2, \dots, c\}$ as all the different positions inside the spectrum where it can be assigned the signal depending on the bit-rate (b_r) and modulation format (m). With an example, for modulation format BPSK and a bit-rate of 40 Gbps, the number of FS required is 4 and $C(m=BPSK, b_r=40)$ represent the c different ways to assigned those 4 consecutive FS in the spectrum represented by

F . Let $p_{c,s}$ be a parameter equal to 1 if the connection $c \in C$ uses the FS $s \in F$ within the spectrum. Then, for all $c \in C(m, b_r)$ the contiguity constraint is implicitly imposed by the proper definition of $p_{c,s}$ such that $\forall i, j \in F : p_{c,i} = 1 = p_{c,j}, i < j \Rightarrow p_{c,k} = 1, \forall k \in \{i, \dots, j\}$. And $\sum_{s \in F} p_{c,s}$ is equal to the amount of FS needed given in Table 2. We denote C as the set of all possible positions for any amount of FS required. So, $C(m, b_r)$ is a subset of C .

For the regeneration aspect, we denote ρ as the capital cost of installing a regenerator in a node $v \in V$.

x_{dpc} a binary decision variable equal to 1 if demand d use primary path segment $p \in P$ with connection c , 0 otherwise.

y_{dbc} a binary decision variable equal to 1 if demand d use backup path segment $b \in B$ with connection c , 0 otherwise.

r_v a binary decision variable that equal to 1 if node $v \in V$ is a regeneration node and 0 otherwise.

$u_{l,j}^s$ a binary decision variable equal to 1 if FS s is used by a demand in edge (i,j) in primary path, 0 otherwise.

$w_{l,j}^s$ a binary decision variable equal to 1 if FS s is used by a demand in edge (i,j) in backup path, 0 otherwise.

The objective function of the model is

$$\text{Min} \sum_{v \in V} \rho r_v + \tau \sum_{(i,j) \in E} \sum_{s \in F} (u_{l,j}^s + w_{l,j}^s)$$



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Subject to the following constraints:

i) Primary Path Flow Conservation Constraints:

$$\sum_{n \in D_i} \sum_{a \in G \in G(d)} x_{dpc} - \sum_{n \in D_i: t_n = i} \sum_{G \in G(d)} x_{dpc} = \begin{cases} 1 & \text{if } \tilde{i} = \underline{S_d} \\ -1 & \text{if } \tilde{i} = \underline{t} \\ 0 & \text{Utherwise} \end{cases} \forall i \in \underline{V}, \forall d \in D$$

ii) Backup Path Flow Conservation Constraints:

$$\sum_{b \in B: B_h = i \in G \in C \in C(d)} y_{dbc} - \sum_{b \in B: t_b = i \in G \in G(d)} y_{dbc} = \begin{cases} 1 & \text{if } \tilde{i} = \underline{s_d} \\ -1 & \text{if } \tilde{i} = \underline{t} \\ 0 & \text{Utherwise} \end{cases} \forall i \in \underline{V}, \forall d \in D$$

iii) Selected primary and backup paths for any connection request must be link disjoint.

$$x_{dpc} + y_{dbc} \leq 1 \quad \forall p \in P; b \in B, c \in C, d \in D$$

iv) The continuity constraint which ensures that only one connection is used for every path– segment and demand in primary and backup path.

$$\sum_{c \in C} x_{dpc} \leq 1 \quad \forall d \in D, p \in P$$

$$\sum_{c \in C} x_{dbc} \leq 1 \quad \forall d \in D, b \in B$$

v) Enforce regeneration requirements by ensuring regeneration at the end of each possible path– segment that does not end in the destination node of the associated demand for primary and backup path.

$$\sum_{p \in P: t_p = v} x_{dpc} \leq r \quad \forall d \in D, c \in C, v \in V \setminus t^d$$

$$\sum_{b \in B: t_b = v} x_{dbc} \leq r \quad \forall d \in D, c \in C, v \in V \setminus t^d$$



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vi) These constraints guarantee that every FS at every link is assigned at most to one demand for primary and backup path.

$$\sum_{p \in P} \sum_{d \in D} \sum_{c \in C(m(p), b_d)} \eta_{i,j,p} p_{c,s} x_{dpc} \leq 1 \forall (i, j) \in E, s \in F$$

$$\sum_{b \in B} \sum_{d \in D} \sum_{c \in C(m(b), b_d)} \eta_{i,j,b} b_{c,s} x_{dbc} \leq 1 \forall (i, j) \in E, s \in F$$

vii) FS s is used by a demand in link (i, j) for primary and backup path.

$$u^s = \sum_{i,j} \sum_{p \in P} \sum_{d \in D} \sum_{c \in C(m(p), b_d)} \eta_{i,j,p} p_{c,s} x_{dpc} \quad \forall (i, j) \in E, s \in F$$

$$w^s = \sum_{i,j} \sum_{b \in B} \sum_{d \in D} \sum_{c \in C(m(b), b_d)} \eta_{i,j,b} b_{c,s} x_{dbc} \quad \forall (i, j) \in E, s \in F$$

5. Performance Comparisons

In this section, several experiments are conducted on a sample network given in Fig. 1 along with three benchmark networks namely NSF network, COST239 network and US network. The specifications of the networks are given in Fig. 3. We implemented the optimization model in IBM ILOG CPLEX ver-12.5 in Dual-Core Intel Core i5 with 8 GB of RAM.

We consider 20 connection requests for the above networks, and demand 100Gbps for each connection request. We generate 10 random set of connection request for the test cases. Pre-computed set of feasible primary and backup path has been used and 4 MFs given in Table-1 has been considered. Fig. 2 shows the average execution time in second of different networks where the large network (US network) unable to completion its execution till 6hours and then after we bound to stop the execution. So, in case of US (large) network the time was not shown in the Fig. 2. In Fig.4 the average number of regenerator placement and average number of FS used in percentage have been projected.



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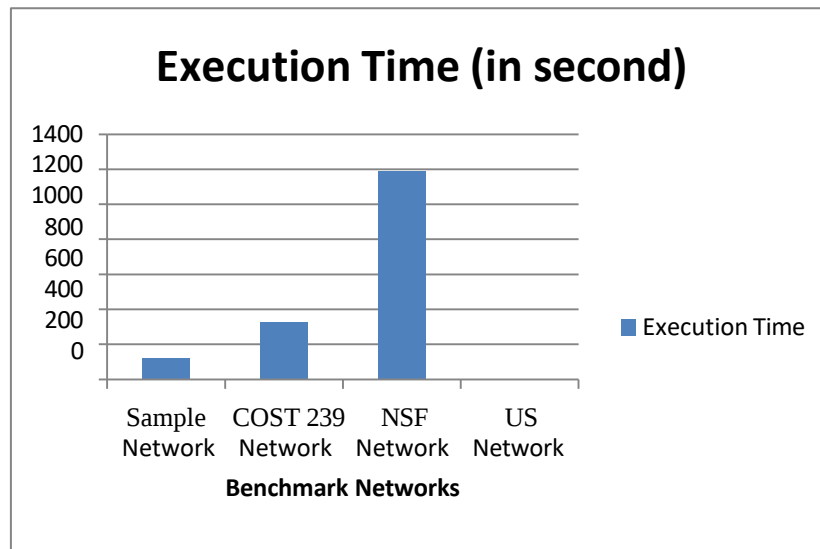


Fig: 2 Execution Time in Second

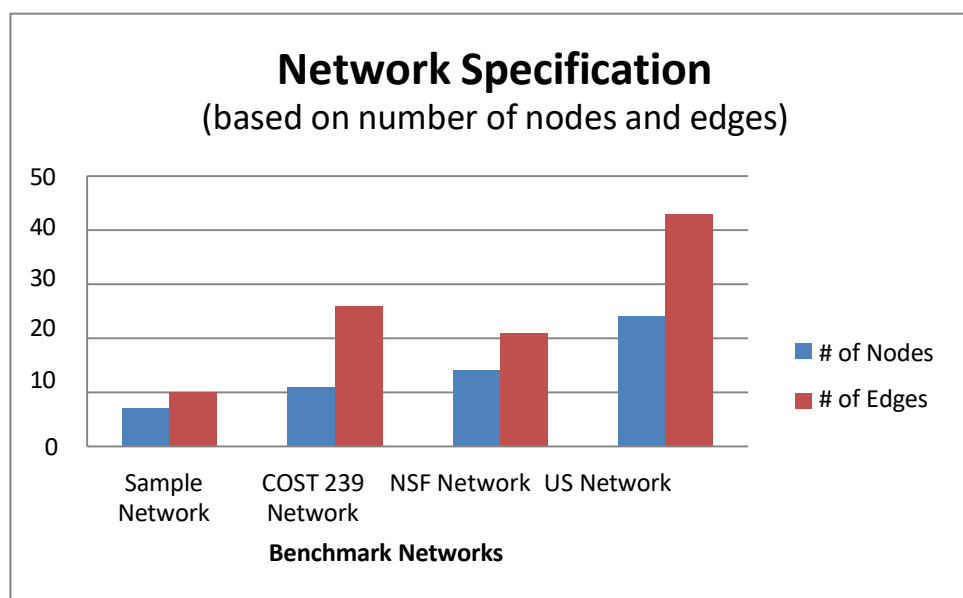


Fig. 3 Different Network Specification (based on the number of nodes and edges)



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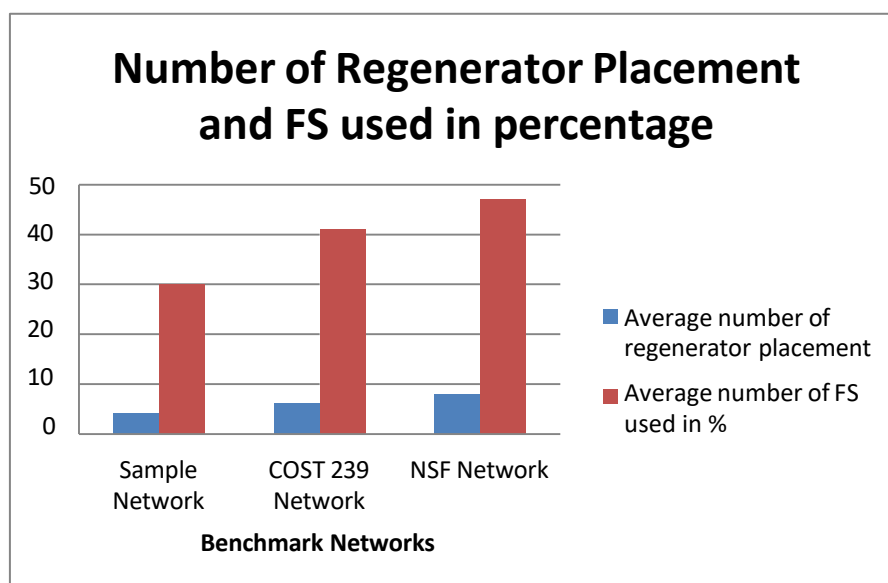


Fig. 4 Comparison of number of regenerator Placement and FS used in percentage

6. Conclusion

This paper proposes an ILP formulation to solve jointly the routing, modulation format, spectrum allocation and regeneration placement problems (known as RSA-RP). The RSA-RP optimization model has been formulated for ST-EONs in static scenario and experimented on three benchmark networks given in Fig. 3.

As ILP model takes much more time for bigger networks and also for large connection request set. So, our future work will be to make an efficient heuristic algorithm which will give near optimal solution as given ILP in small networks. So, the proposed ILP model will help to compare the optimal result with a heuristic algorithm which will be our future work.

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