Green Field Capacity Planning

For Deployment Of Resources In Optical Networks

Report submitted to the SASTRA deemed to be University as the

requirement for the course

B. Tech. Electronics & Communication Engineering
ECE 300-Mini Project

Submitted by

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Signature of Project Supervisor : S. Baskaran

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Date : 05-05-2025

Project Vivavoce held on 05.05.2025

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Declaration

We declare that the thesis title **"Green Field Capacity Planning For Deployment Of Resources In Optical Networks"** submitted by us in an original work done by us under the guidance of **Mr.S.Baskaran Asst.Professor-II/ECE,Srinivasa Ramanujan Centre,SASTRA Deemed to be University** during the 6th semester of the academic year 2024-25,in the **Srinivasa Ramanujan Centre.** The work is original and wherever We have used materials from other sources,we have given due credit and cited them in the text of the thesis.This thesis has not formed the basis for the award of any degree,diploma,associate-ship,fellowship or other similar title to any candidate of any university.

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A.Harshith Sankar

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Date : 05-05-2025

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ABSTRACT

The growing complexity and traffic in metro and core optical networks necessitate efficient capacity planning to optimize resources and control costs. Traditional static capacity planning, based on fixed-cycle upgrades and predetermined allocations, often leads to overprovisioning, underutilization, and unnecessary expenses. This study proposes a static capacity planning framework using elastic optical networks (EONs) and bandwidth-variable transponders (BVTs) with a fixed-allocation strategy to minimize both capital (CapEx) and operational expenditures (OpEx). A single-layer optimization mathematical model is developed to optimize resources over a predefined planning period, considering technology advancements and equipment depreciation. Simulations with realistic scenarios highlight the framework's effectiveness in managing static traffic demands and its cost-efficiency compared to traditional methods.

Keywords: Elastic Optical Networks (EONs), Bandwidth-Variable Transponders (BVTs), Flow Path Algorithm, Static Traffic Modeling.

ABBREVIATIONS

EON- Elastic Optical Networks

BVT-Bandwidth-Variable Transponders

CapEx-Capital Operational Expenditures

OpEx-Operational Expenditures

SDN-Software-Defined Networking

WDM-Wavelength Division Multiplexing

FPA-Flow Path Algorithm

JOM-Java Optimization Modeler

ATM-Asynchronous Transfer Mode

MPLS-Multi Protocol Label Switching

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CHAPTER-1

INTRODUCTION

Optical networks serve as the backbone for fast, high-speed, and high-bandwidth data transmission, facilitating seamless global connectivity. The significant rise in data traffic, propelled by technological advancements such as 5G, cloud computing, and the Internet of Things (IoT), has created considerable demands on network infrastructure. Effective capacity planning and efficient resource allocation in optical networks are essential for meeting these challenges. The initiative titled "Green Field Capacity Planning for Deployment of Resources in Optical Networks" aims to formulate an innovative framework that optimizes resource usage, improves network scalability, and guarantees strong performance in optical communication systems.

The core objective of this initiative is to devise a methodology for green field capacity planning, which entails constructing an optical network from the ground up to adequately fulfill both present and future traffic demands. In contrast to conventional network planning, which primarily concentrates on upgrading pre-existing infrastructure, green field planning provides the advantage of designing a customized, optimized network structure. This strategy is particularly applicable to new deployments in underserved regions, data centers, or next-generation telecommunications networks. Key focuses of this project include bandwidth distribution, alleviating congestion, and ensuring fault tolerance through the use of mathematical modeling techniques, flow path algorithms, traffic normalization approaches, among others. By leveraging tools like Net2Plan and optimization models in Java, the solution becomes practical and flexible for assessing network designs and their performance.

The approach taken is thorough and comprehensive, encompassing the development of a Java-based optimization model, the application of a flow path algorithm, and a detailed investigation into network requirements and traffic behaviors. The model utilizes flow path theory as the foundation for an effective capacity planning strategy. To evaluate the efficacy of the proposed method, Net2Plan is utilized to design and assess a 5-node network scenario for practical applications. The project integrates advanced traffic modeling strategies, including traffic matrix normalization, to ensure an even load distribution and avert network bottlenecks. Through the combination of technologies like Software-Defined Networking (SDN) and Wavelength Division Multiplexing (WDM), the system boosts the network's efficiency and responsiveness, paving the way for future-ready optical networks.

This initiative holds significant importance as it will tackle fundamental challenges in optical network design, including scalability, resource optimization, and dynamic traffic management. The outcomes signify maximized resource utilization, intelligent traffic navigation, and a scalable network framework capable of supporting future growth. The analysis of these results highlights the project's aim to "develop robust, adaptable systems that can manage varying traffic demands without compromising performance." By referencing research by Papanikolaou et al. and Klinkowski et al., the initiative aligns with the most recent advancements in elastic optical networks and network optimization tools such as Net2Plan. This introduction lays out a framework for exploring the methodology, outcomes, and implications, while also accentuating the project's role in enhancing optical networking.

In summary, this initiative represents a significant advancement in addressing the complexities of capacity planning within optical networks. By integrating theoretical principles with practical implementation, it establishes a strong framework for developing network architectures that are not only efficient but also resilient and scalable. The following sections will present a detailed overview of the project's contributions to optical communication systems, encompassing methodology, results, and interpretations.

CHAPTER-1.1

OBJECTIVE

Optimized Capacity Planning

• Develop a static capacity planning framework for metro and core optical networks using EONs and BVTs.

• Utilize the Flow Path Algorithm (FPA) for efficient spectrum allocation, scalability, and cost-effectiveness.

Efficient Routing Optimization

• Use Net2Plan with FPA-based routing to minimize congestion, overprovisioning, and spectrum fragmentation.

• Adapt dynamically to traffic variations and network constraints.

Cost-Effective Optimization Model

• Develop a single-layer model to optimize network deployment and operational expenses using FPA-based traffic

engineering.

• Improve cost efficiency by considering technology advancements, equipment lifecycle, and resource utilization.

Empirical Validation – Simulate realistic network scenarios to validate the framework, demonstrating better cost

efficiency, spectrum utilization, and network resilience compared to traditional methods.

CHAPTER-1.2

EXISTING SYSTEM:

The Old Way of Planning Networks

Imagine running a network like a factory with a fixed production line. Traditional methods rely on static capacity planning, where resources are pre-allocated, and upgrades happen on a rigid schedule. This approach has some serious drawbacks:

Wasted Resources: It's like buying a huge fridge and only using half the space. Networks are often overprovisioned, meaning you're paying for bandwidth you don't need.

Inefficiency: Resources sit idle, leading to underutilization. It's like having extra staff on shift with nothing to do.

High Costs: Building and maintaining this setup racks up big bills—both for equipment (CapEx) and ongoing operations (OpEx).

No Flexibility: These systems can't adjust on the fly to sudden spikes in demand, like a restaurant unable to handle a rush of customers. Upgrades are costly and planned without real-time data.

Basic Tools: There's little use of smart algorithms or automation. It's like planning a road trip with a paper map instead of GPS—manual and prone to errors.

CHAPTER-1.3

PROPOSED SYSTEM:

A Smarter, Modern Approach

Java-Powered Brain: A custom model built in Java uses flow path theory and math to allocate resources like a master chef perfectly portioning ingredients nothing goes to waste.

Elastic Optical Networks (EONs): Instead of rigid channels, EONs are like stretchy fabric, flexibly allocating spectrum to fit the exact need, cutting down on wasted space.

Bandwidth-Variable Transponders (BVTs): These are like adjustable faucets, letting you dial up or down the bandwidth as needed. You only pay for what you use, growing the network as demand rises.

Net2Plan Simulations: Think of this as a virtual sandbox where engineers can test network designs, tweak routing, and predict performance before making real-world changes.

Flow Path Algorithm: This is the network's GPS, finding the best routes for data and balancing the load so no part of the system gets overwhelmed.

Mathematical Precision: Using Integer Linear Programming (ILP), the system analyzes traffic patterns like a super-smart accountant, ensuring every resource is used optimally.

Tech-Savvy Integration: With Software-Defined Networking (SDN) and automation, the network runs more smoothly, scaling up or down like a well-oiled machine.

CHAPTER-2

TOOLS AND ENVIRONMENT

CHAPTER 2.1:

SOFTWARE REQUIREMENT:

1. Language : Java 1.8
2. Platform : windows 11

CHAPTER 2.2:

REQUIRED TOOLS:

1. Net2Plan
2. Eclipse

1. **Net2Plan** is a free, open-source Java-based software tool designed for the planning, optimization, and evaluation of communication networks, including optical networks. It provides a flexible, technology-agnostic framework that supports the development, testing, and simulation of network design algorithms. Net2Plan is widely used in academia and industry for network planning tasks, such as capacity dimensioning, traffic routing, and resilience analysis, and it integrates with external solvers like CPLEX or GLPK through the Java Optimization Modeler (JOM) library

- Created a Java-based model in Net2Plan to plan optical network capacity, using a 5-node network example. Designed an offline network with two implementation planes for efficient traffic
- Flow Path Algorithm: Integrated a Flow Path Algorithm in Net2Plan to route traffic accurately in a 5-node network, ensuring optimal performance and resource use.

2. **Eclipse**: Eclipse is a free, open-source IDE for Java development, offering customizable tools like code completion, debugging, and plugins, ideal for network planning projects.

- Java Development for Optimization Model: Eclipse enables efficient coding of the Java-based optimizing model in Net2Plan, with features like code completion and refactoring to manage the 5-node network's two-plane design.
- Net2Plan Integration: Eclipse simplifies adding Net2Plan's libraries (e.g., WDMUtils, JOM) to the Java Build Path, supporting optimization algorithms for capacity allocation and traffic routing.

CHAPTER 2.3:

RESOLVER

GLPK:

Easy Integration with Net2Plan and Eclipse:

Net2Plan uses GLPK as its default solver for linear programs (defaultILPSolver: glpk). In Eclipse, you add GLPK's library (e.g., glpk-java.jar) to the Java Build Path, allowing your Java code to call GLPK through JOM for solving optimization tasks.

GLPK's Java interface (via GLPK-Java) simplifies its use project, letting that focus on coding the model and algorithm without worrying about solver details.

CHAPTER-3

ANALYSIS AND WORKING DESIGN

CHAPTER-3.1

Literature Survey

S. No	Title of the Paper	Author & Year	Technique Used	Description
1.	A Survey on Elastic Optical Networks: Principles and Challenges	M. Klinkowski, K. Walkowiak (2021)	Survey-based study analyzing existing research on EONs, comparing architectures, and discussing future challenges	Discusses Elastic Optical Networks (EONs) and their advantages over fixed-grid WDM networks. Covers Bandwidth-Variable Transponders (BVTs), spectrum flexibility, and cost efficiency.
2	Net2Plan: An Open-Source Tool for Optical Network Design and Optimization	P. Pavon-Marino, J. García-Haro (2019)	Java-based network simulation, Optimization algorithms for routing and resource allocation	Introduces Net2Plan, the Java-based tool you are using in your project. Explains how it can be applied for traffic routing, capacity planning, and performance evaluation,making it directly relevant.
3	Elastic Optical Networks	George N. Rouskas (2024)	Mathematical modeling and optimization techniques to develop algorithms for efficient routing and spectrum assignment, considering factors such as traffic demands and network topology	Investigates energy-efficient strategies for routing and spectrum assignment in EONs. Focuses on optimizing resource allocation to minimize energy consumption while maintaining network performance.

Tabel-3.1

CHAPTER-3.2:

Methodology:

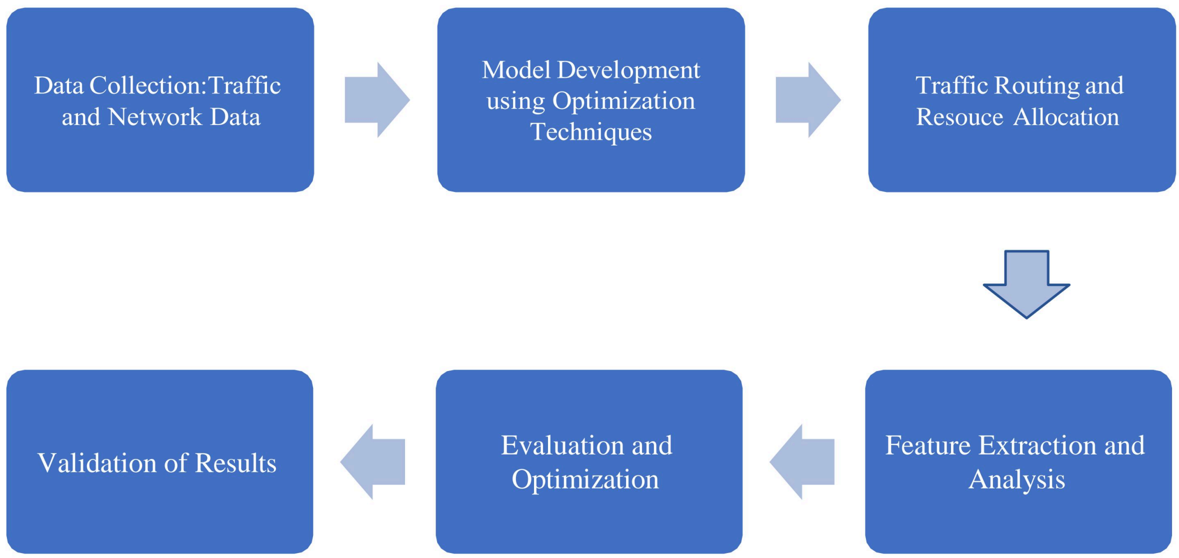

Fig-3.1

1. Data Collection: Traffic and Network Data: Gather relevant data for capacity planning in optical networks.Process: Collect traffic demand data, node information, and link capacities from a simulated or real-world optical network environment using a 5-node example and the traffic matrix.Details: Use tools like Net2Plan to simulate network topology and traffic demands, ensuring the data represents realistic network scenarios.

2. **Model Development Using Optimization Techniques**: Develop a model to optimize resource allocation in the optical network. Process: Build a Java-based optimization model utilizing flow path theory and mathematical formulations (e.g., Integer Linear Programming - ILP) to plan capacity.Formulate the problem to minimize congestion and maximize resource utilization.Incorporate constraints like bandwidth limits, node capacities, and link availability.Implementation: Implement the model in Net2Plan with two planes of implementation—design and traffic routing.

3. **Traffic Routing and Resource Allocation**: Ensure efficient traffic routing and resource allocation.Process: Integrate a flow path algorithm into the model to route traffic accurately across the network.Analyze demands, nodes, and links to ensure optimal paths.Apply traffic

normalization techniques to balance the load and prevent bottlenecks.Details: Use the ILP traffic matrix to analyze traffic demands across different modes.

4. **Feature Extraction and Analysis**: Extract key features to evaluate network performance.Process: Identify critical metrics such as total normalized traffic, node efficiency, and link capacity from the traffic matrix and network design.Analyze the traffic demands between nodes.Evaluate resource utilization to ensure minimal congestion.

5. **Evaluation and Optimization** : Assess the model's performance and optimize the network design.Process:Calculate performance metrics like traffic routing efficiency, load distribution, and fault tolerance.Compare the model's output with expected outcomes to validate the design.Iterate on the model by adjusting parameters to improve scalability and adaptability, supporting future expansion.

6. **Validation of Results**: Validate the optimized network design.Process: Use the results from the traffic matrix and normalization to confirm that the network design achieves balanced load distribution and efficient resource utilization.Check for seamless data flow and minimal bottlenecks, aligning with the project's goals of intelligent path selection and traffic routing efficiency

CHAPTER-3.3

ALGORITHM

Flow-Path Formulation:

In flow-based networks, the flow-path algorithm is a routing technique that assigns a particular path through the network to each demand or traffic flow. By effectively managing network resources, it optimizes performance by guaranteeing that every flow takes a predetermined path.

$\max_{x,u_u}$ u_u subject to:

$$\lambda\_d : \sum_{p} \in \square\_d \, x_p = h\_d, \quad \forall\ d \in \mathcal{D}$$
$$\pi_e : \sum_{p} \in \square_e \, x_p \leq u_e - u_u, \quad \forall\ e \in \mathcal{E}$$

Flow-path routing works by assigning a specific set of possible paths to each demand in the network. These paths are the only ones allowed to carry traffic for that demand. Every path is linked to a unique demand, ensuring that traffic follows a predictable and structured route.

The network consists of a collection of possible paths, with some paths passing through specific links. To determine how much traffic each path should carry, a decision variable is assigned to regulate the flow efficiently.

One key approach in flow-path routing is minimizing congestion by maximizing the worst-case unused bandwidth in the links. This means ensuring that even under the heaviest traffic conditions, there is always some spare capacity available to prevent bottlenecks.

To define the network, we use a set of nodes and links, each with a specific capacity. The incoming traffic comprises multiple demands, typically uni-cast transmissions. The fundamental rule states that all traffic must be carried—meaning the sum of traffic in the selected paths for a demand should match its total offered traffic.

Another critical aspect is that the total traffic passing through a given link must not exceed its capacity, minus an amount representing the worst-case scenario of unused bandwidth. In other words, the network should still function smoothly even if some capacity is reserved to handle unexpected conditions.

Lastly, ensures that no path carries a negative amount of traffic, enforcing logical and realistic traffic distribution across the network.

$$X_p = (\text{Amount of traffic of demand } d(p) \text{ carried by } p) \quad , \forall p \in \mathbb{P}$$

Important Features:

Dedicated Paths: Reliability and predictability are ensured by each flow following a predetermined, distinct path through the network.

Connection-Oriented Routing: The precise routing path is established at the connection establishment phase prior to the start of data transmission.Centralized Path Selection: Depending on traffic demand and general network conditions, the network nodes setup and control routing paths.

This technique is frequently employed in networks that use Frame Relay, ATM (Asynchronous Transfer Mode), and MPLS (Multi protocol Label Switching), where routing tables are dynamically modified in response to traffic demands.

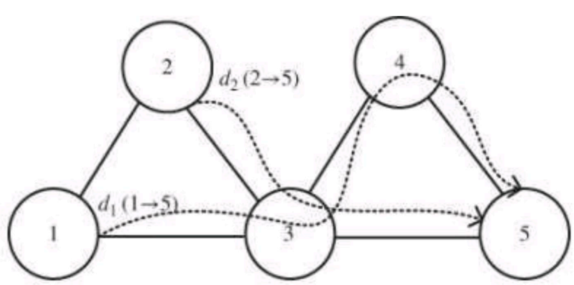

Fig-3.2

CHAPTER-3.4

ADVANTAGES:

- **Better Use of Network Resources**
  It makes sure bandwidth is used where it's really needed, avoiding waste.
- **Scales Easily for the Future**
  As more people use the internet, your system can grow and handle it without major upgrades.
- **Smarter Traffic Flow**
  It finds the best paths for data to travel, so everything moves faster and more smoothly.
- **Cost Savings**
  Helps companies avoid spending too much on hardware and energy —
  more efficient = more savings.
- **Energy Efficient**
  Uses less power by adjusting bandwidth dynamically, which is great for both the environment and operating costs.

CHAPTER-3.5

DIS-ADVANTAGES:

- **Takes Time to Set Up**
  It's a bit complex and needs good technical knowledge to get started.
- **Relies Heavily on Simulation Tools**
  Without tools like Net2Plan, it's hard to test and validate the setup.
- **Not Real-Time**
  The model is designed for planning — it can't quickly react to unexpected network failures or issues.
- **Requires Special Equipment**
  Needs modern hardware like bandwidth-variable transponders, which older networks may not have.
- **High Learning Curve**
  The math and logic behind it (like flow path algorithms) can be tough for beginners to understand.

CHAPTER-3.6

APPLICATIONS:

1. Building a Better Internet in Cities

Your project helps design networks that move internet traffic faster and more efficiently, like planning the perfect road map so there's no traffic jam.

2. Helping Telecom Companies Plan Smarter

Big telecoms (like Airtel, Jio) can use your model to figure out exactly where and how much network they need, saving money and avoiding waste.

3. Keeping Data Centers in Sync

Data centers (where the internet lives) need to talk to each other super fast. Your system helps them stay connected smoothly, even when things get busy.

4. Making 5G Work Better

5G needs super-strong and fast back-end support. Your model helps build that invisible backbone so your phone has faster internet with less lag.

5. Speeding Up Cloud & Streaming Whether it's Netflix, YouTube, or Google Drive, your work helps route that data faster

6. and more efficiently, so things load quicker and smoother.

CHAPTER - 4

RESULTS

Traffic Matrix designed with user given offered traffic (Before capacity planning):

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

List view | Traffic matrix view

Number of entries: 14

Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
21	0	Madrid	Barcelona	undefined	undefined	5.08	0	1		0	✓
22	1	Madrid	Valencia	undefined	undefined	4.81	0	1		0	✓
23	2	Madrid	Sevilla	undefined	undefined	4.53	0	1		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	7.66	0	1		0	✓
25	4	Barcelona	Madrid	undefined	undefined	3.16	0	1		0	✓
26	5	Barcelona	Valencia	undefined	undefined	4	0	1		0	✓
27	6	Barcelona	Sevilla	undefined	undefined	8.75	0	1		0	✓
28	7	Barcelona	Zaragoza	undefined	undefined	7.77	0	1		0	✓
29	8	Valencia	Madrid	undefined	undefined	5.72	0	1		0	✓
30	9	Valencia	Barcelona	undefined	undefined	4.8	0	1		0	✓
31	10	Valencia	Sevilla	undefined	undefined	5.04	0	1		0	✓
32	11	Valencia	Zaragoza	undefined	undefined	3.34	0	1		0	✓
33	12	Sevilla	Madrid	undefined	undefined	1.03	0	1		0	✓
34	13	Sevilla	Barcelona	undefined	undefined	7.95	0	1		0	✓
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Fig-4.1

View/Edit network state | Offline algorithms | Online simulation | What-if analysis | View reports

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

List view | Traffic matrix view

Number of entries: 20

Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
21	0	Madrid	Barcelona	undefined	undefined	8.83	5.08	0.43		0	✓
22	1	Madrid	Valencia	undefined	undefined	0.76	4.81	0		0	✓
23	2	Madrid	Sevilla	undefined	undefined	1.45	4.53	0		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	16.85	7.66	0.55		0	✓
25	4	Barcelona	Madrid	undefined	undefined	4.8	3.16	0.34		0	✓
26	5	Barcelona	Valencia	undefined	undefined	11.57	4	0.65		0	✓
96	6	Madrid	Barcelona	undefined	undefined	0.73	0	1		0	✓
97	7	Madrid	Valencia	undefined	undefined	7.48	0	1		0	✓
98	8	Madrid	Sevilla	undefined	undefined	14.7	0	1		0	✓
99	9	Madrid	Zaragoza	undefined	undefined	10.75	0	1		0	✓
100	10	Barcelona	Madrid	undefined	undefined	13.27	0	1		0	✓
101	11	Barcelona	Valencia	undefined	undefined	20.3	0	1		0	✓
102	12	Barcelona	Sevilla	undefined	undefined	4.67	0	1		0	✓
103	13	Barcelona	Zaragoza	undefined	undefined	12.06	0	1		0	✓
104	14	Valencia	Madrid	undefined	undefined	8.81	0	1		0	✓
105	15	Valencia	Barcelona	undefined	undefined	8.07	0	1		0	✓
106	16	Valencia	Sevilla	undefined	undefined	13.96	0	1		0	✓
107	17	Valencia	Zaragoza	undefined	undefined	18.26	0	1		0	✓
108	18	Sevilla	Madrid	undefined	undefined	3.26	0	1		0	✓
109	19	Sevilla	Barcelona	undefined	undefined	19.43	0	1		0	✓
---	---	---	---	---	---	200	29.25	---	---	---	0

Fig-4.2

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

List view | Traffic matrix view

Number of entries: 20

Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
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23	2	Madrid	Sevilla	undefined	undefined	28.71	1.45	0.95		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	26.59	16.85	0.37		0	✓
25	4	Barcelona	Madrid	undefined	undefined	28.68	4.8	0.83		0	✓
26	5	Barcelona	Valencia	undefined	undefined	31.98	11.57	0.64		0	✓
282	6	Madrid	Barcelona	undefined	undefined	1.65	0	1		0	✓
283	7	Madrid	Valencia	undefined	undefined	5.16	0	1		0	✓
284	8	Madrid	Sevilla	undefined	undefined	24.33	0	1		0	✓
285	9	Madrid	Zaragoza	undefined	undefined	6.28	0	1		0	✓
286	10	Barcelona	Madrid	undefined	undefined	11.2	0	1		0	✓
287	11	Barcelona	Valencia	undefined	undefined	30.49	0	1		0	✓
288	12	Barcelona	Sevilla	undefined	undefined	29.7	0	1		0	✓
289	13	Barcelona	Zaragoza	undefined	undefined	2.59	0	1		0	✓
290	14	Valencia	Madrid	undefined	undefined	17.42	0	1		0	✓
291	15	Valencia	Barcelona	undefined	undefined	32.09	0	1		0	✓
292	16	Valencia	Sevilla	undefined	undefined	32.8	0	1		0	✓
293	17	Valencia	Zaragoza	undefined	undefined	19.91	0	1		0	✓
294	18	Sevilla	Madrid	undefined	undefined	12.16	0	1		0	✓
295	19	Sevilla	Barcelona	undefined	undefined	29.89	0	1		0	✓
---	---	---	---	---	---	400	44.26	---	---	---	0

Fig-4.3

View/Edit network state | Offline algorithms | Online simulation | What-if analysis | View reports

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

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22	1	Madrid	Valencia	undefined	undefined	33.18	24.34	0.27		0	✓
23	2	Madrid	Sevilla	undefined	undefined	19.72	28.71	0		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	18.09	26.59	0		0	✓
25	4	Barcelona	Madrid	undefined	undefined	43.36	28.68	0.34		0	✓
26	5	Barcelona	Valencia	undefined	undefined	14.64	31.98	0		0	✓
382	6	Madrid	Barcelona	undefined	undefined	35	0	1		0	✓
383	7	Madrid	Valencia	undefined	undefined	27.46	0	1		0	✓
384	8	Madrid	Sevilla	undefined	undefined	31.95	0	1		0	✓
385	9	Madrid	Zaragoza	undefined	undefined	40.4	0	1		0	✓
386	10	Barcelona	Madrid	undefined	undefined	17.25	0	1		0	✓
387	11	Barcelona	Valencia	undefined	undefined	40.19	0	1		0	✓
388	12	Barcelona	Sevilla	undefined	undefined	17.49	0	1		0	✓
389	13	Barcelona	Zaragoza	undefined	undefined	3.41	0	1		0	✓
390	14	Valencia	Madrid	undefined	undefined	25.33	0	1		0	✓
391	15	Valencia	Barcelona	undefined	undefined	41.17	0	1		0	✓
392	16	Valencia	Sevilla	undefined	undefined	27.81	0	1		0	✓
393	17	Valencia	Zaragoza	undefined	undefined	18.51	0	1		0	✓
394	18	Sevilla	Madrid	undefined	undefined	2.89	0	1		0	✓
395	19	Sevilla	Barcelona	undefined	undefined	22.76	0	1		0	✓
---	---	---	---	---	---	500	144.33	---	---	---	0

Fig-4.4

Traffic network network after execution of Flow path algorithm:

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

List view | Traffic matrix view

Number of entries: 14

Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
21	0	Madrid	Barcelona	undefined	undefined	5.08	5.08	0		0	✓
22	1	Madrid	Valencia	undefined	undefined	4.81	4.81	0		0	✓
23	2	Madrid	Sevilla	undefined	undefined	4.53	4.53	0		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	7.66	7.66	0		0	✓
25	4	Barcelona	Madrid	undefined	undefined	3.16	3.16	0		0	✓
26	5	Barcelona	Valencia	undefined	undefined	4	4	0		0	✓
27	6	Barcelona	Sevilla	undefined	undefined	8.75	8.75	0		0	✓
28	7	Barcelona	Zaragoza	undefined	undefined	7.77	7.77	0		0	✓
29	8	Valencia	Madrid	undefined	undefined	5.72	5.72	0		0	✓
30	9	Valencia	Barcelona	undefined	undefined	4.8	4.8	0		0	✓
31	10	Valencia	Sevilla	undefined	undefined	5.04	5.04	0		0	✓
32	11	Valencia	Zaragoza	undefined	undefined	3.34	3.34	0		0	✓
33	12	Sevilla	Madrid	undefined	undefined	1.03	1.03	0		0	✓
34	13	Sevilla	Barcelona	undefined	undefined	7.95	7.95	0		0	✓
---	---	---	---	---	---	73.65	73.65	---	---	---	0

Fig-4.5

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

List view | Traffic matrix view

Number of entries: 20

Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
21	0	Madrid	Barcelona	undefined	undefined	8.83	8.83	0		0	✓
22	1	Madrid	Valencia	undefined	undefined	0.76	0.76	0		0	✓
23	2	Madrid	Sevilla	undefined	undefined	1.45	1.45	0		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	16.85	16.85	0		0	✓
25	4	Barcelona	Madrid	undefined	undefined	4.8	4.8	0		0	✓
26	5	Barcelona	Valencia	undefined	undefined	11.57	11.57	0		0	✓
96	6	Madrid	Barcelona	undefined	undefined	0.73	0.73	0		0	✓
97	7	Madrid	Valencia	undefined	undefined	7.48	7.48	0		0	✓
98	8	Madrid	Sevilla	undefined	undefined	14.7	14.7	0		0	✓
99	9	Madrid	Zaragoza	undefined	undefined	10.75	10.75	0		0	✓
100	10	Barcelona	Madrid	undefined	undefined	13.27	13.27	0		0	✓
101	11	Barcelona	Valencia	undefined	undefined	20.3	20.3	0		0	✓
102	12	Barcelona	Sevilla	undefined	undefined	4.67	4.67	0		0	✓
103	13	Barcelona	Zaragoza	undefined	undefined	12.06	12.06	0		0	✓
104	14	Valencia	Madrid	undefined	undefined	8.81	8.81	0		0	✓
105	15	Valencia	Barcelona	undefined	undefined	8.07	8.07	0		0	✓
106	16	Valencia	Sevilla	undefined	undefined	13.96	13.96	0		0	✓
107	17	Valencia	Zaragoza	undefined	undefined	18.26	18.26	0		0	✓
108	18	Sevilla	Madrid	undefined	undefined	3.26	3.26	0		0	✓
109	19	Sevilla	Barcelona	undefined	undefined	19.43	19.43	0		0	✓
---	---	---	---	---	---	200	200	---	---	---	0

Fig-4.6

Traffic link capacity change:

Network | Layer 0

General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

Number of entries: 14

Id	Index	Show/hide	A	B	Bidirection...	Up?	Trav. QoS...	Total QoS ...	QoS sched...	Coupled d...	Capacity ()	Occupied ...	Carried tr...	Utilization	Length (km)	Prop. spee...
7	0	✓	Madrid	Barcelona	undefined	✓		0	{}	undefined	100	28.99	28.99	0.29	504.65	200000
8	1	✓	Madrid	Valencia	undefined	✓		0	{}	undefined	100	8.24	8.24	0.08	301.92	200000
9	2	✓	Madrid	Sevilla	undefined	✓		0	{}	undefined	100	20.82	20.82	0.21	391.43	200000
10	3	✓	Madrid	Zaragoza	undefined	✓		0	{}	undefined	100	45.86	45.86	0.46	272.44	200000
11	4	✓	Barcelona	Madrid	undefined	✓		0	{}	undefined	100	22.74	22.74	0.23	504.65	200000
12	5	✓	Barcelona	Valencia	undefined	✓		0	{}	undefined	100	31.87	31.87	0.32	303.36	200000
13	6	✓	Barcelona	Zaragoza	undefined	✓		0	{}	undefined	100	12.06	12.06	0.12	256.51	200000
14	7	✓	Valencia	Madrid	undefined	✓		0	{}	undefined	100	27.07	27.07	0.27	301.92	200000
15	8	✓	Valencia	Barcelona	undefined	✓		0	{}	undefined	100	8.07	8.07	0.08	303.36	200000
16	9	✓	Valencia	Sevilla	undefined	✓		0	{}	undefined	100	13.96	13.96	0.14	540.56	200000
17	10	✓	Sevilla	Madrid	undefined	✓		0	{}	undefined	100	22.69	22.69	0.23	391.43	200000
18	11	✓	Sevilla	Valencia	undefined	✓		0	{}	undefined	100	0	0	0	540.56	200000
19	12	✓	Zaragoza	Madrid	undefined	✓		0	{}	undefined	100	0	0	0	272.44	200000
20	13	✓	Zaragoza	Barcelona	undefined	✓		0	{}	undefined	100	0	0	0	256.51	200000
---	---	0	---	---	---	0	0	0	---	---	1400	242.36	242.36	---	5141.76	---

Fig-4.7

Network | Layer 0

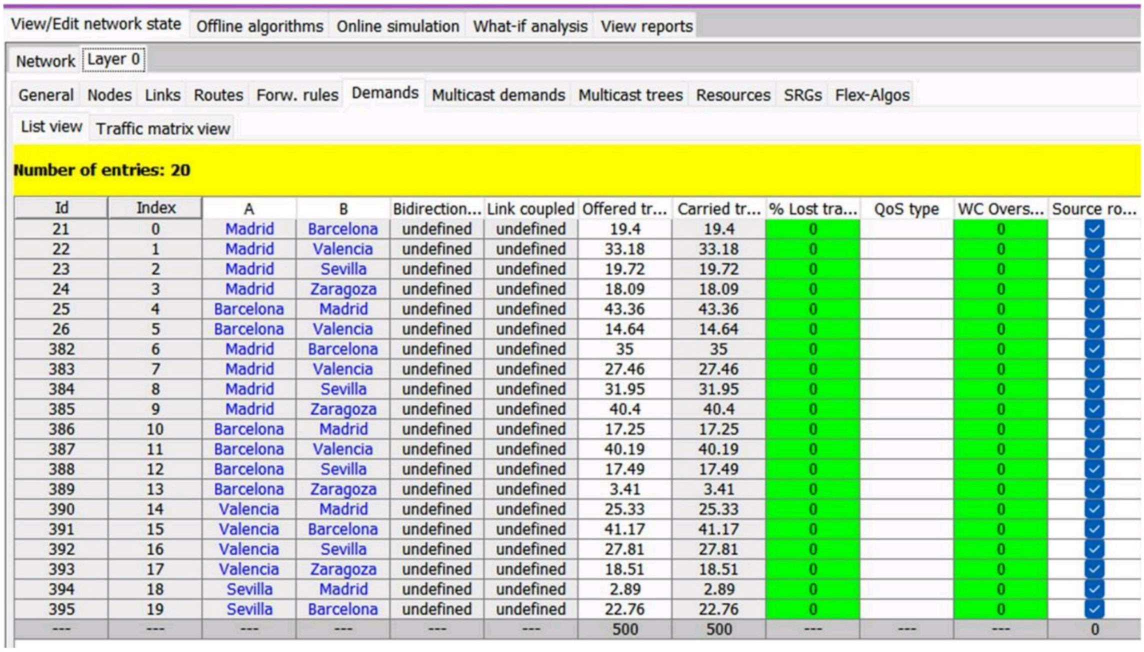
General | Nodes | Links | Routes | Forw. rules | Demands | Multicast demands | Multicast trees | Resources | SRGs | Flex-Algos

List view | Traffic matrix view

Number of entries: 20

Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
21	0	Madrid	Barcelona	undefined	undefined	4.04	4.04	0		0	✓
22	1	Madrid	Valencia	undefined	undefined	24.34	24.34	0		0	✓
23	2	Madrid	Sevilla	undefined	undefined	28.71	28.71	0		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	26.59	26.59	0		0	✓
25	4	Barcelona	Madrid	undefined	undefined	28.68	28.68	0		0	✓
26	5	Barcelona	Valencia	undefined	undefined	31.98	31.98	0		0	✓
282	6	Madrid	Barcelona	undefined	undefined	1.65	1.65	0		0	✓
283	7	Madrid	Valencia	undefined	undefined	5.16	5.16	0		0	✓
284	8	Madrid	Sevilla	undefined	undefined	24.33	24.33	0		0	✓
285	9	Madrid	Zaragoza	undefined	undefined	6.28	6.28	0		0	✓
286	10	Barcelona	Madrid	undefined	undefined	11.2	11.2	0		0	✓
287	11	Barcelona	Valencia	undefined	undefined	30.49	30.49	0		0	✓
288	12	Barcelona	Sevilla	undefined	undefined	29.7	29.7	0		0	✓
289	13	Barcelona	Zaragoza	undefined	undefined	2.59	2.59	0		0	✓
290	14	Valencia	Madrid	undefined	undefined	17.42	17.42	0		0	✓
291	15	Valencia	Barcelona	undefined	undefined	32.09	32.09	0		0	✓
292	16	Valencia	Sevilla	undefined	undefined	32.8	32.8	0		0	✓
293	17	Valencia	Zaragoza	undefined	undefined	19.91	19.91	0		0	✓
294	18	Sevilla	Madrid	undefined	undefined	12.16	12.16	0		0	✓
295	19	Sevilla	Barcelona	undefined	undefined	29.89	29.89	0		0	✓
---	---	---	---	---	---	400	400	---	---	---	0

Fig-4.8



Id	Index	A	B	Bidirection...	Link coupled	Offered tr...	Carried tr...	% Lost tra...	QoS type	WC Overs...	Source ro...
21	0	Madrid	Barcelona	undefined	undefined	19.4	19.4	0		0	✓
22	1	Madrid	Valencia	undefined	undefined	33.18	33.18	0		0	✓
23	2	Madrid	Sevilla	undefined	undefined	19.72	19.72	0		0	✓
24	3	Madrid	Zaragoza	undefined	undefined	18.09	18.09	0		0	✓
25	4	Barcelona	Madrid	undefined	undefined	43.36	43.36	0		0	✓
26	5	Barcelona	Valencia	undefined	undefined	14.64	14.64	0		0	✓
382	6	Madrid	Barcelona	undefined	undefined	35	35	0		0	✓
383	7	Madrid	Valencia	undefined	undefined	27.46	27.46	0		0	✓
384	8	Madrid	Sevilla	undefined	undefined	31.95	31.95	0		0	✓
385	9	Madrid	Zaragoza	undefined	undefined	40.4	40.4	0		0	✓
386	10	Barcelona	Madrid	undefined	undefined	17.25	17.25	0		0	✓
387	11	Barcelona	Valencia	undefined	undefined	40.19	40.19	0		0	✓
388	12	Barcelona	Sevilla	undefined	undefined	17.49	17.49	0		0	✓
389	13	Barcelona	Zaragoza	undefined	undefined	3.41	3.41	0		0	✓
390	14	Valencia	Madrid	undefined	undefined	25.33	25.33	0		0	✓
391	15	Valencia	Barcelona	undefined	undefined	41.17	41.17	0		0	✓
392	16	Valencia	Sevilla	undefined	undefined	27.81	27.81	0		0	✓
393	17	Valencia	Zaragoza	undefined	undefined	18.51	18.51	0		0	✓
394	18	Sevilla	Madrid	undefined	undefined	2.89	2.89	0		0	✓
395	19	Sevilla	Barcelona	undefined	undefined	22.76	22.76	0		0	✓
---	---	---	---	---	---	500	500	---	---	---	0

Fig-4.9

Before Execution of Flow path algorithm

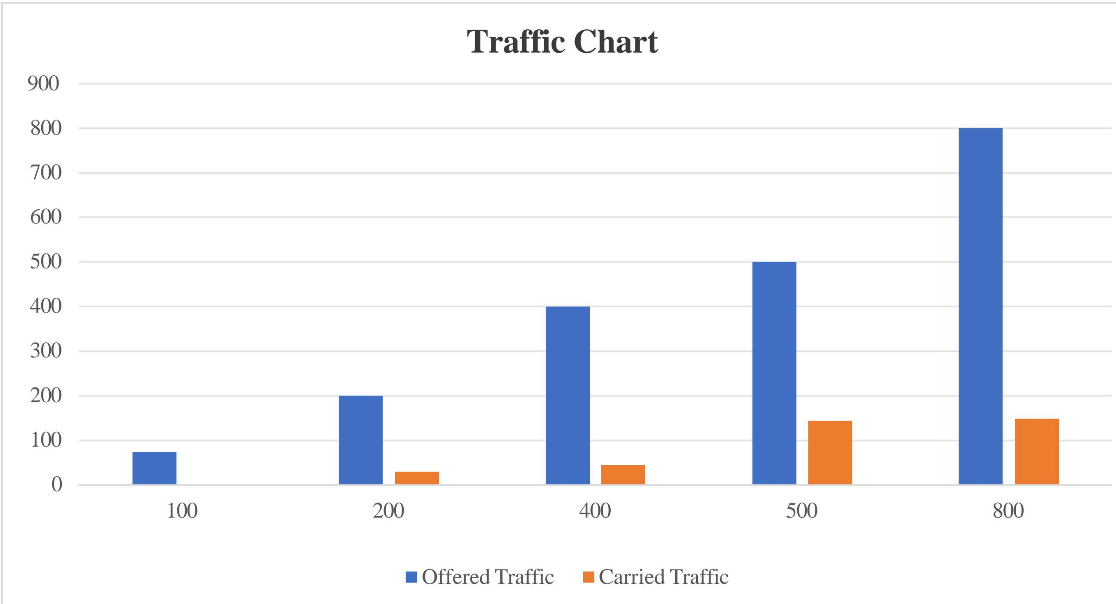


Fig-4.10

After Execution of Flow path algorithm

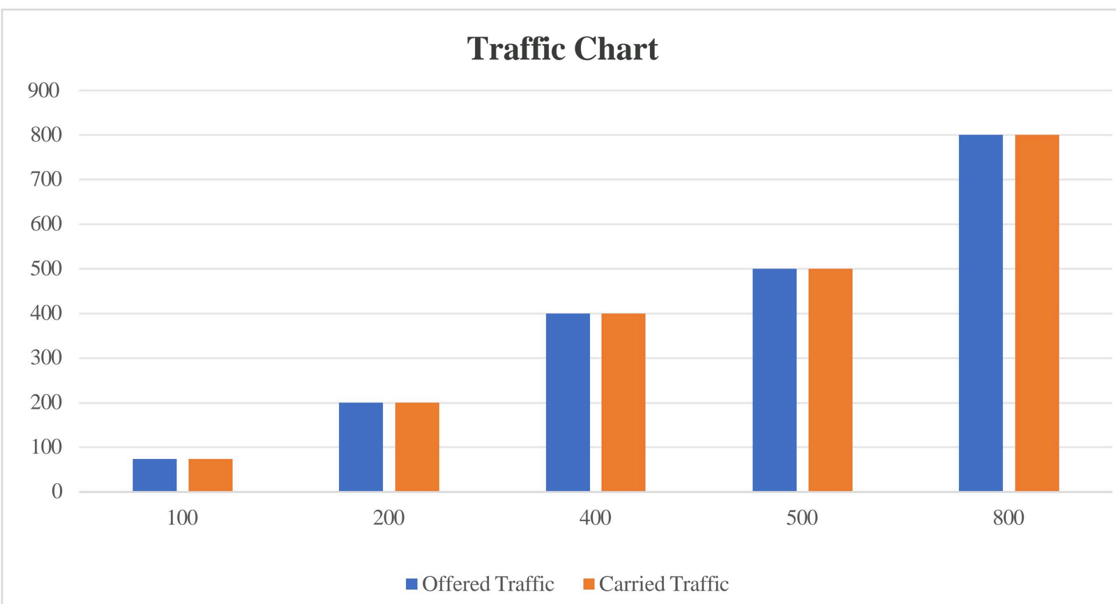


Fig-4.11

CHAPTER - 5

CONCLUSION AND FUTURE PLAN

In this project, we tackled the challenge of Green Field Capacity Planning for optical networks, focusing on how to efficiently deploy resources from scratch. Our approach revolved around an optimization model designed to make the most of available resources while ensuring traffic demands are met without unnecessary excess capacity. This balance is key—not just for cost-effectiveness, but also for the long-term sustainability of network infrastructure.

At its core, our framework creates a strategic foundation for rolling out optical networks in a way that prioritizes both efficiency and scalability. What's exciting is that this model isn't rigid—it can be adapted for real-world applications, including complex multi-layer networks and dynamic traffic patterns. This means our work directly contributes to smarter, more adaptive network planning methodologies that will be crucial for the future of high-speed optical communications.

We specifically focused on metro and core optical networks, leveraging Elastic Optical Networks (EONs) and Bandwidth-Variable Transponders (BVTs) to maximize flexibility. Using Net2Plan as a simulation platform and integrating the Flow Path Algorithm (FPA), we built a Java-based optimization model that addressed key challenges like spectrum allocation, efficient routing, and resource management.

Our methodology followed a structured approach, starting with mathematical modeling, then testing a 5-node network, integrating FPA, and finally validating results through traffic matrix normalization. The results were promising—showcasing better bandwidth utilization, reduced congestion, and improved traffic engineering, all while keeping the network adaptable and energy-efficient.

Ultimately, this project proves that our static capacity planning framework offers significant advantages over traditional fixed-grid WDM networks, both in terms of cost and spectral efficiency. By incorporating Software-Defined Networking (SDN) concepts and ILP-based modeling, we've added even more intelligence and adaptability to optical network planning. With these advancements, we lay the groundwork for smarter, more scalable networks in the years to come.

CHAPTER-6

REFRENCES

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CHAPTER-7

APPENDIX

Incremental Planning of Multi-layer Elastic Optical Networks

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***Abstract*— Traditionally, network upgrade cycles are long and performed independently for the IP edges and the optical transport layers. The traffic in metro and core networks is forecasted to grow in volume but also in dynamicity and the network operators face the challenge of shorter upgrades, influencing the cost efficiency and suppressing the return of investment. Thus, it is imminent to adopt a multi-period network planning approach and account jointly for the upgrade of the optical but also the IP edges of the network. In this work we formulate the problem of the incremental joint multi-layer planning of an IP over elastic optical network (EON) and propose an ILP formulation to solve it. Our objective is to deploy in a period the minimum additional network resources to cope with the changed traffic (CapEx) from the previous period, but also to minimize the changes for the transition between the two periods (OpEx). Simulation results based on realistic network scenarios validate the proposed planning approach.**

***Index Terms*—Elastic optical networks; incremental capacity planning; joint multi-layer network planning.**

I. Introduction

We are witnessing a significant change in Internet usage with multimedia traffic, mainly video, and cloud services, occupying the major share of the available capacity. These services have a high peak-to-average ratio, and exhibit quite dynamic changes with respect to time and location [1]. Future 5G networks will engender a wide range of new services with extreme requirements, such as ultrahigh-definition video streaming, augmented and virtual reality, cloud gaming, smart homes, etc. For the evolution toward 5G, it is envisioned that optical networking will play a major role in supporting the requirements, while reducing the deployment costs [2].

According to the conventional approach, optical transport networks have long upgrade cycles. In order to ensure that the resulting network design can cope with future traffic until the next upgrade cycle, the capacity is overprovisioned with some forecast. Nevertheless, these forecasts fail to capture traffic dynamicity and changes that heavily influence cost efficiency (equipment cost decrease due to technology maturation). Moreover, another factor that contributes to overprovisioning is that the optical network and the IP edges are upgraded independently. Capacity overprovisioning, results in underutilized equipment and unnecessary investments for long periods of the network lifecycle.

To meet the increasing and more dynamic traffic requirements telecom operators are facing the problem of shorter upgrade cycles which suppress the return of investment (ROI). The introduction of Elastic Optical Networks (EON) and bandwidth variable transponders (BVT), enable a re-configurable optical network [3]. Combining EON with the IP layer re-configurability can facilitate a pay-as-you-grow approach, where few equipment is installed and continuously re-optimized and upgraded in shorter cycles. However, this has to be done in a coordinated manner for both IP and optical segments.

Multi-layer network optimization [4 - 6] and multi-period network planning [7 - 11] have been active research subjects in the last few years. Design algorithms for IP over (elastic or fixed) optical networks have received a great deal of attention. In [4] the authors highlight the fundamental role played by the design process in optimizing the base IP topology and introduce router bypass that leads to significant cost savings. In order to reduce the aggregation level of the incoming flows the authors in [5] exploit the EON technology's finer granularity to allow grooming at the optical layer. Taking advantage of that, they propose a new architecture to design national IP/MPLS networks interconnected through an EON core. The authors in [6] examine the planning problem of a multi-layer IP over EON from the perspective of CapEx minimization taking into account modular IP/MPLS routers at the optical network edges along with BVTs.

Multi-period planning is an eminent approach to obtain cost optimization for transport networks in a long term time frame. There are two approaches for multi-period planning, (i) global optimization assuming knowledge of the traffic for all periods [7 - 8], or (ii) incremental planning [9 - 11]. Authors in [7] incorporate multi-layer and multi-period planning in a single optimization step. In their attempt to study the migration scenario from a networking point of view, authors in [8] propose a single-layer ILP model. Multi-period planning is used to study the migration from 10G to 40G services and investigate the optimal deployment channel mix as a function of the reach and equipment prices.

To quantify the degree of traffic dynamics and growth that justify the higher initial investment in (flex-rate) BVT technology the authors in [9] propose an ILP model. This model performs multi-period analysis that accounts for the requirements for hardware provisioning in multiple periods with increasing traffic. In order to achieve savings compared to current provisioning practice with End-of-Life physical layer margins, the authors in [10] present an algorithm that provisions lightpaths considering the actual physical performance and use it in a multi-period planning scenario to postpone equipment deployment. In a similar concept the authors in [11] model the progressive ageing of the transmission channel and quantify the benefits of dynamically adjusting the BVT to the physical network quality.

between 9% and 29% when compared to *Inc* and savings that range between 4% and 14% when compared to *Inc-ML*. The savings are slightly lower compared to CapEx due to deployment of more regenerators for Inc and Inc-ML for long paths, which provide wavelength conversion possibilities.

B. Lightpaths establishment analysis and cost breakdown

In this section we focus on capturing the trade-off between CapEx minimization of the equipment used in the current state and the minimization of OpEx associated with the equipment displacements and reconfigurations between network states. Figures 3.a and b presents the number of reconfigured and added lightpaths per period, respectively. As stated, *J-ML* is agnostic to the previous state of the network, leading to the optimum CapEx achieved through an extensive reconfiguration of already established lightpaths. Figure 3.a shows that the proposed joint incremental multi-layer *J-Inc-ML* approach limits the number of lightpath reconfigurations and establishing of new lightpaths, and consequently controls the corresponding OpEx. The proposed technique (*J-Inc-ML*) achieves a significant reduction, of the order of 50%, of the reconfiguration processes, while maintaining a relatively small number of added lightpaths per period, which is only 18% larger than the one achieved by *J-ML* (Fig. 3.b).

(a)

(b)

(c)

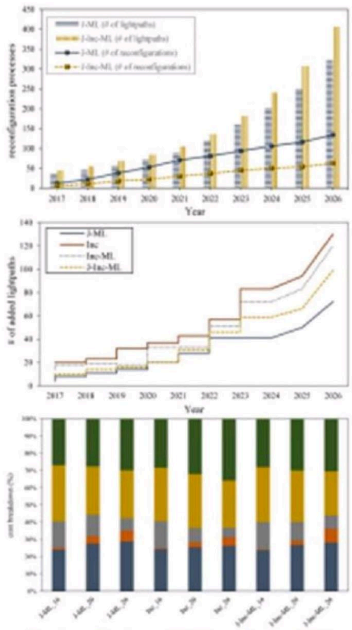

Fig. 3. (a) Reconfiguration overhead in the optical layer for J-ML and J-Inc-ML scenarios, (b) number of added lightpaths per period and (c) cost breakdown of the network for J-ML, Inc, Inc-ML and J-Inc-ML scenarios.

No significant differences are observed in the cost breakdown for the three planning scenarios (Fig. 3.c), which is expected as uniform cost decrease is assumed for all layers. Only in the *J-Inc-ML* case an increase in the cost of the regenerators is depicted, which arises as a result of the deployment of more translucent paths that in turn result to IP ports reduction. What is also interesting to note for the *Inc* approach is the increased cost for the router chassis for medium and high traffic which comes as a result of the increased number of transponders (and consequently IP ports) that leads to the deployment of multi-chassis configurations.

V. Conclusions

The inevitable growth of the traffic to be transported by optical backbone networks, both in volume and in dynamicity cause tremendous pressure on network infrastructures, accentuating the need for planning methods that increment the capacity of optical networks in timely manner. In view of this, planning the network in an incremental multi-layer approach was proposed in this paper. Through an ILP formulation we exploit optimally the reconfigurability of BVTs and modular IP/MPLS router architectures, with the objective being the minimization of the added equipment (CapEx) at each period and the equipment displacements and re-configurations (OpEx) in two consecutive periods. We evaluated the performance under realistic network scenarios and verified that the proposed solution can tradeoff network equipment reconfiguration for CapEx.

Acknowledgment

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(denoted as *J-ML*).

▪ Incrementally plan the network without being able to perform any change from the previous network state (denoted as *Inc*). This restriction applies to both IP and optical layers, limiting the transponder reconfiguration and IP grooming capabilities.

▪ Incrementally plan jointly the multi-layer network to optimize both the added equipment (CapEx) at each period and the number of changes made (OpEx), using the proposed algorithm (Section III). We examined two scenario variations, by varying the parameter W_d which controls the ability to deviate from the previous network state: W_d=0 (denoted as *Inc-ML*), and W_d =0.5 (denoted as *J-Inc-ML*). When W_d=0 (*Inc-ML*), the model is not able to perform any change in the optical layer (*lightpaths*) of the previous network state. When W_d =0.5 (*J-Inc-ML*) the model equally optimizes the CapEx of the added equipment and the OpEx associated with the transition changes between the two states.

In our simulations we used the Deutsche Telekom topology (DT), so that the results obtained are representative of real networks. The traffic matrix of the DT network is realistic as provided by the operator (DTAG) in [15]. The traffic was projected from year 2016 for 10 years, with a step of 1 year, assuming a uniform 35% increase per year.

TABLE I
BANDWIDTH VARIABLE TRANSPONDERS

BVT 1				BVT 2			
Capacity (Gb/s)	Reach (km)	Data slots	cost (a.u.)	Capacity (Gb/s)	Reach (km)	Data slots	cost (a.u.)
[illegible]	[illegible]	4		[illegible]	[illegible]	7	
[illegible]	[illegible]	4		[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	5		[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	5	[illegible]	[illegible]	[illegible]	11	[illegible]
[illegible]	[illegible]	6		[illegible]	[illegible]	12	
[illegible]	[illegible]	6		1000	[illegible]	14	
[illegible]	[illegible]	6		[illegible]			

We assume that each link of the reference networks is a single fiber with 360 spectrum slots of 12.5 GHz width. We assumed that there are available 2 types of BVTs, the first with maximum rate of 400 Gbps and the second of 1 Tbps, the later was made available after year 2020. The transmissions configuration (tuples) of the BVTs are presented in TABLE I. The cost of BVTs and the cost model of IP/MPLS routers are based on the cost models defined by IDEALIST project [15]. We view an IP/MPLS router as a modular device, built out of (single or multi) chassis. A chassis provides a specified number of bi-directional slots with a nominal transmission speed. Into each router slot, a linecard of the corresponding speed can be installed. Each linecard provides a specified number of ports at a specified speed and occupies one slot of the IP/MPLS router. We assumed that for every BVT configuration there is an available linecard type. We also consider a scalable multi-chassis core router, with up to 72 chassis, and a 16 router slot capability per chassis.

In order to estimate accurately the incremental cost of the equipment used during the entire network lifecycle we have to consider technology maturation, which leads to depreciation of the equipment over time. In our study we assume a depreciation of 10% per year for all equipment.

A. Capital Expenditure and spectral impact

In this section we compare the different planning scenarios with respect to the cost (Fig. 2.a) and spectral resource utilization (Fig. 2.b). We use *J-ML* as benchmark for the comparison, since planning the network from scratch without taking into account the previous network state obviously leads to the optimum (lowest) CapEx, but it is not a realistic approach. The *Inc* technique, due to its inability to fully exploit the reconfigurability of the IP and optical equipment exhibits in all periods, the worst performance. The *J-Inc-ML* approach jointly considers multi-layer and incremental planning, introducing a penalty on the reconfiguration of existing lightpaths. By adjusting the reconfiguration penalty we examine the trade-off between CapEx minimization of equipment used in each period and OpEx associated with the equipment displacements and reconfigurations between the network states.

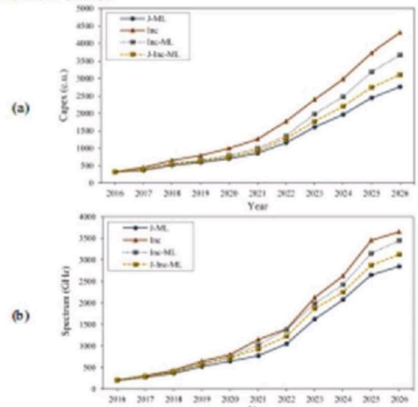

Fig. 2. (a) Evolution of capital expenditure per period, (b) maximum spectrum used per period for years 2016-2026.

More specifically, Fig. 2.a shows that *J-Inc-ML* achieves CapEx savings that range between 15% and 38% when compared to *Inc* and savings that range between 5% and 18% when compared to *Inc-ML*. The savings come from the limited reconfiguration capabilities of the *Inc* and *Inc-ML* at both or only the optical layers, respectively. Note that the savings increase as time advances since the bad choices made by *Inc* and *Inc-ML* aggregate and are not corrected as time advances. Moreover, the proposed *J-Inc-ML* solution adds equipment when required, taking advantage of price depreciations. Note that the difference between *Inc* and *Inc-ML* is that the later allows reconfiguration at the IP layer (grooming). As IP-layer equipment comprises up to 70% of the total CapEx, savings on the IP-layer are deemed more significant in a multi-period perspective. Taking as reference the *J-ML* that achieves the optimal CapEx (plans the network from scratch without taking into account the previous state), we observe that the proposed *J-Inc-ML* solution achieves CapEx close to the optimal. Note that the proposed solution tradeoffs network equipment reconfiguration for CapEx. By appropriate selecting W_d parameter, we can find solutions with CapEx ranging from the highest achieved by the *Inc* scenario to the lowest achieved by the *J-ML* scenario, with a wide or limited network reconfiguration, respectively (as discussed in the next Subsection).

Similarly to the CapEx metric, Fig. 2.b shows that the proposed *J-Inc-ML* achieves spectrum savings that range

v_{nb} Integer variables, equal to the number of deployed transponders of type b at node n.

d_{pt} Integer variables, equal to the number of removed (p,t) tuples from the previous state.

c Float variable, equal to the cost of network equipment.

Constants:

F'^{p}_{sd} Integer constants, equal to the IP traffic of end-nodes s to d that is transferred over optical path p in the previous network state.

X'_{pt} Integer constants, equal to the number of lightpaths of path-transmission tuple pairs (p,t) used in the previous network state.

Θ'_{nb} Integer constants, equal to the number of transponders of type b at node n used in the previous network state.

Objective:

$$\min\left(W_C \cdot c + (1-W_C)\cdot z\right) \tag{1}$$

- Cost calculation constraints:

$$c = W_d \cdot \left(\sum_{n\in V}\sum_{b\in B} C_b \cdot v_{nb} + \sum_{n\in V}\sum_{h\in H} C_h \cdot y_{nh} + \sum_{n\in V} C_{LCC}\cdot q_n + \sum_{n\in V} C_{CH}\cdot o_n\right) + (1-W_d)\cdot \sum_{p\in P}\sum_{t\in T\Pi(p,t)} d_{pt} \tag{2}$$

- IP flow continuity constraints:

$\forall\ (s,d)\in V^2, n\in V$

$$\left(\sum_{n\in V}\sum_{p\in P_{in}} f^{p}_{sd} - \sum_{n\in V}\sum_{p\in P_{nj}} f^{p}_{sd}\right) = \begin{cases} -\Lambda_{sd},\ n=s \\ \Lambda_{sd},\ n=d \\ 0,\ \ n\neq s,d \end{cases} \tag{3}$$

- Path-transmission tuple assignment constraints:

$\forall (i,j)\in V^2$

$$\sum_{sd\in V^2} f^{p}_{sd} \le \sum_{p\in P_{ij}}\sum_{t\in T\Pi(p,t)} (R_t \cdot x_{pt}) \tag{4}$$

- Previous state constraints (*optical layer*):

$\forall\ feasible(p,t)$

$$d_{pt} \ge X'_{pt} - x_{pt} \tag{5}$$

- Utilized transponders constraints:

$\forall n\in V, b\in B$

$$\theta_{nb} = \sum_{p\ starts\ at\ n}\sum_{t\in T_b} x_{pt} \tag{6}$$

- Deployed transponders constraints:

$\forall n\in V, b\in B$

$$v_{nb} \ge \theta_{nb} \tag{7}$$

$$v_{nb} \ge \Theta'_{nb} \tag{8}$$

- Previous state constraints (*IP layer*):

$\forall (s,d)\in V^2, (i,j)\in V^2, p\in P_{ij}\ |\ F'^{p}_{sd} > 0,$

$$f^{p}_{sd} > F'^{p}_{sd} \tag{9}$$

- Maximum spectrum slot used constraints:

(z^l equals to the maximum indexed spectrum slot used in each bidirectional fiber link)

$\forall l\in L, (i,j)\in V^2,$

$$z^l = \sum_{p\in P_{ij}, l\in p}\ \sum_{t\in T\Pi(p,t)} (S_t \cdot x_{pt}) \qquad z = \max(z^l) \qquad z \le Z \tag{10}$$

- Number of line-cards per node constraints:

$\forall n\in V, h\in H$

$$y_{nh} \ge \sum_{b\ is\ supported\ by\ h} v_{nb} / N_h \tag{11}$$

- Number of line-card chassis per node constraints:

$$q_n \ge \sum_h y_{nh} / N_{LCC},\ \forall n\in V \tag{12}$$

- Number of fabric card chassis per node constraints:

$$o_n \ge q_n / N_{CH},\ \forall n\in V \tag{13}$$

The joint multi-layer planning ILP formulation presented above dimensions the network for normal operation. The algorithm creates the solution by choosing among k (pre-calculated) optical paths P_{ij} between optical nodes i,j. Apart from other variables, we assume that the solution includes values for IP flow variables f^{p}_{sd}, which identify the amount of IP traffic of end-nodes s to d that is transferred over optical path p. Variables x_{pt} may correspond to a lightpath (p,t) that serves transparently an end-to-end demand between the given source s (=i) and destination d (=j), or to a series of lightpaths that compose a translucent connection. The cost of the IP/MPLS routers is captured through variables y_{nh}, q_n and o_n. The objective is to minimize a weighted sum of the maximum spectrum and the cost of the equipment used in both layers (Eq. 1). The cost function (Eq. 2) is chosen as the weighted sum of the variables capturing the CapEx of the equipment used in both layers of the network in the current state and the variables representing the number of removed (p,t) path-transmission tuples from the previous state (Eq. 6), which capture the OpEx associated with the transponders displacements or re-configurations. Constraints (3), (4) and (10)–(13) deal with the joint multi-layer planning problem, while constraints (5)–(9) address the incremental planning problem.

In order to reduce the model complexity and obtain optimal results for realistic network sizes, the ILP only ensures that the maximum spectrum slot used in the network (z) is within the range of the available spectrum slots (Z) in Eq. (10). So in the above ILP model we do not perform the spectrum assignment. The model can be extended to jointly perform that, but the gains in optimization were observed to be small. So for simplicity and to enable to run the ILP model in large network instances, the spectrum assignment is performed in a subsequent step using a modified Hungarian method [14].

IV. Performance Results

In this section we evaluate the performance of the incremental multilayer planning algorithm presented in Section III. In particular, we compare the following three scenarios:

- Plan the whole network from scratch at each period, without taking into account the previous network state previous state of the network at t_{N-1}, including the state of the resources (established lightpaths and IP tunnels) and information about physical resources (installed/available equipment and its location). The optimization process jointly considers the previous network state and both its layers with the objective being the minimization of both the added network equipment (CapEx) and the equipment displacements and re-configuration between the two successive network states (OpEx).

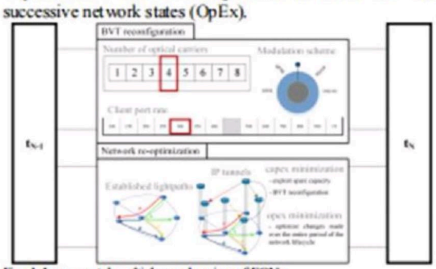

Fig. 1. Incremental multi-layer planning of EONs.

As shown in Fig. 1 the proposed model exploits the flexibility of BVTs that can be used in numerous different configurations to carry client traffic. This allows an initial design that is scalable through the years, since it is possible to increase client's port rate by increasing, when available, the number of optical carriers or by using higher order modulation formats. This would be applied in subsequent periods, combined possible with the addition of regenerators (since higher order modulation formats entail a decrease in the optical reach) and the possible displacement of the already installed ones. Additionally, network resources can be made available by re-optimization of the previous network state exploiting the IP grooming capabilities to enable spare capacity utilization.

The proposed model jointly considers multi-layer and incremental planning, taking into account technology maturation and price reductions. In order to achieve cost savings through incremental network planning it is essential to adopt short network cycles, which are able to capture the effects of traffic dynamicity and avoid overprovisioning by incorporating small but frequent network updates. The challenge is therefore to optimize the changes made, minimizing the costs incurred over the entire period of the network lifecycle.

III. Mathematical Formulation

In the ILP model presented below multi-layer and multi-period planning are jointly considered in a single optimization step. For each period both network layers are simultaneously optimized by taking into account the previous network state. The extend to which the current state will commit to the previous one is controlled through a parameter, W_d, passed as input to the model.

We assume that the network is represented by a graph $G(V,L)$, with V being the set of nodes and L the set of bidirectional fiber links connecting two locations. The nodes of the the graph correspond to the optical nodes of the network on which we also account for the cost of the IP/MPLS connected router. We are also given the traffic matrix Λ, where Λ_{sd} corresponds to IP demanded capacity between nodes (s,d). We are also given the model of the IP/MPLS routers (chassis and line-cards) and the transmission capabilities of the transponders, described in what are called transmission-tuples. Each tuple t represents a specific configuration of the transponder (rate, spectrum) and is related to a specific transmisison reach, taking into account a model for the optical physical layer (e.g. GN model [13]). The network designs are based on pre-calculated optical paths. In particular, we assume that for each 2 pair of nodes (i,j) we precalculate k-paths which define the set P_{ij}. We also assume that a path-transmission tuple (p,t) is feasible either if the transmission reach of tuple t is higher than the length of the path p, or by placing regenerators over the path at the node before quality of transmission (QoT) becomes unacceptable.

The inputs of the problem are stated in the following:

- The network topology represented by graph $G(V,L)$.
- The maximum number Z of available spectrum slots (of 12.5 GHz)
- The traffic described by the traffic matrix Λ.
- A set B of the available transponders (BVTs).
- A set T of feasible transmission tuples, which represent the transmission options of the available transponders, with tuple $t=(D_t,R_t,S_t,C_t)$ indicating feasibility of transmision at distance D_t, with rate R_t (Gpbs), using S_t spectrum slots, for the transponder of cost C_t. Also, T_b represents the transmission tuples of transponder $b \in B$.
- A set of line-cards represented by H, where a line-card for transponder $b \in B$ is represented by a tuple $h_b=(N_h,C_h)$, where N_h is the number of transponders of type b that the line-card supports.
- The IP/MPLS router cost, specified by a modular cost model. We assume that an IP/MPLS router consists of line-card chassis of cost C_{LCC}, that suport N_{LCC} line-cards each, and fabric card chassis of cost C_{FCC}, that suport N_{FCC} line-card chassis.
- The weighting coefficient, W_C, taking values between 0 and 1. Setting $W_c = 1$ minimizes solely the cost whereas setting $W_c \approx 0$ minimizes the maximum spectrum used.
- The weighting coefficient, W_d, taking values between 0 and 1. Setting $W_d = 1$ minimizes solely the current state cost ignoring the previous network state, whereas setting $W_d \approx 0$ maintains the previous state lightpaths and minimizes any additional cost to that.

Variables:

- f_{sd}^{p} Float variables, equal to the rate of the IP tunnel from IP source s to destination d that passes over a lightpath that uses path p.
- x_{pt} Integer variables, equal to the number of lightpaths of path-transmission tuple pairs (p,t) used.
- y_{nh} Integer variables, equal to the number of line-cards of type h at node n.
- q_n Integer variables, equal to the number of line-card chassis at node n.
- o_n Integer variables, equal to the number of fabric-card chassis at node n.
- z Integer variable, equal to the maximum indexed spectrum slot.
- θ_{nb} Integer variables, equal to the number of utilized transponders of type b at node n.

In this paper, we take an incremental planning approach for the joint planning of a multi-layer IP over EON network. We adopt an incremental approach, since traffic is becoming more dynamic and unpredicted with the advent of new services and 5G technology. Thus, it seems hard to have a priori knowledge of the exact traffic at intermediate periods for the entire network lifecycle, but rather good forecasts for short-term volume growth. Our objective is to deploy at each period the minimum amount of additional network resources so that we are able to cope with traffic changes from the previous period, optimizing both the capital expenditure (CapEx) of the equipment used and the operational expenditure (OpEx) associated with the changes imposed by the transition between the two periods. Taking into account aspects such as technology maturation and equipment depreciation we can use the developed solution to perform what-if studies and identify the right times for introducing new technologies and implementing appropriate changes on the network.

Even though multi-layer network optimization and multi-period network planning were extensively researched, there is no formal description and optimal solution of the combination of these planning approaches, to the best of our knowledge. The main novelties of this work are the following. Firstly, we propose an optimization model that jointly considers multi-layer and incremental planning. Secondly, the proposed model introduces a penalty on the reconfiguration of existing lightpaths, to restrict the extent of modifications performed between periods. Thirdly, the problem definition and the proposed optimization model is quite general, can be used for planning of an IP over optical network with any mix or fixed or tunable transponders. The model takes as input realistic transmission specifications and considers quite accurately the IP layer, through a detailed model for the IP/MPLS routers deployed at the edges of the optical network.

The rest of the paper is organized as follows. In Section II we formally state the incremental planning of a multi-layer IP over EON problem. Section III describes the mathematical formulation of the ILP model to solve the problem. Performance results are presented in Section IV. Our conclusions follow in Section V.

II. Problem Statement

In this section we describe the architecture of the multilayer IP over elastic optical network (EON) and define the incremental planning problem of such a network.

A. IP-over-Elastic Optical Network Architecture

We assume an EON domain that consists of optical switches and fiber links. The fiber links consist of SMF spans and EDFAs. The optical switches function as Reconfigurable Optical Add Drop Multiplexers (ROADMs) employing the flex-grid technology, and support optical connections (lightpaths) of one or more contiguous 12.5 GHz spectrum slots. Note that the solutions to be proposed will also be valid for fixed-grid WDM networks (50 GHz wavelengths), which can be considered as a special and simpler case of EONs. At each optical switch, none, one or more IP/MPLS routers are connected, which comprise the edges of the optical domain. An IP/MPLS router is connected to the ROADM via a grey transceiver. Bandwidth Variable Transponders (BVTs) are plugged to the ROADMs to transform the client signal for optical long-haul transmission.

The transponder, functioning as a transmitter, transforms the electrical packets coming from the IP source router to optical signals (E/O conversion). Then the traffic entering the ROADM is routed over the optical network in all-optical connections (lightpaths). We assume that a number of transmission parameters of the BVTs and the regenerators are under our control, affecting the rate and reach at which they can transmit. The lightpath passes transparently or translucently (if the use of regenerators is required) intermediate ROADM and reaches the lightpaths' destination ROADM where it is dropped. Note that this can be the final destination or an intermediate hop in this domain. The signal is converted back to electrical at the transponder that functions as the optical receiver (O/E conversion) and the packets are forwarded and handled by the corresponding IP/MPLS router. We assume that lightpaths are bidirectional and thus in the above description an opposite directed lightpath is also installed, and the transponders act simultaneously as transmitters and receivers. The same applies to the grey transceivers and the router ports. If the IP/MPLS router that is reached is the final destination of the IP/MPLS connection in the domain, the packets are forwarded to the next domain. If it is an intermediate hop, the packets are re-routed back to the optical network, over a new lightpath and through possible more intermediate IP/MPLS router hops towards the domain destination.

From the optimization point of view, the network consists of two layers, the IP (or virtual) layer and the optical (or physical) layer. The optical lightpaths are installed taking into account the physical topology, and create the virtual topology, on top of which the IP/MPLS connections are installed.

B. Incremental Multi-layer Network Planning

For considering the operation time horizon of a network, there are two planning approaches: (i) global and (ii) incremental. In this study we focus on incremental planning. We assume that the upgrade process of the multi-layer network is performed periodically and takes decision on how to support the traffic for the next planning period, given the current state of the network. So, the assumption is that this process is performed successively and separately for each period, having the knowledge of only the traffic of the next period and no further future knowledge.

Traditionally, optical networks have long upgrade cycles. Due to the forecasts used for long periods spare capacity is installed, the system is utilized below its actual performance leading to a significant increase in network expenditures. Moreover, overprovisioning is also due to different cycles in IP and the optical layers upgrades. Since long and independent cycles fail to capture emerging traffic requirements, in this work we adopt an incremental short-cycle multi-layer planning approach. Few equipment is installed at both IP and optical layers and the network is continuously re-optimized and upgraded.

In the initial planning period (Period t_0) both (IP and optical) layers are simultaneously optimized with the objective being the minimization of the cost. Algorithms such as [12], can be used for this step. Assuming a period t_N the incremental model takes as input the new traffic and the

B31 PLAG

by M Sudha

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