

Routing, Modulation Level, Spectrum and Multiwavelength Transponder Assignment in IP-over-EON – Integer Linear Programming and Genetic Algorithm Approaches

Santiago M. Ortiz, Miguel León

Universidad Nacional de Asunción, Facultad Politécnica

San Lorenzo, Paraguay

{santiortizpy, amigleon92}@fpuna.edu.py

and

Luis G. Moré, José Colbes, Diego P. Pinto-Roa

Universidad Nacional de Asunción, Facultad Politécnica

San Lorenzo, Paraguay

{lmore, jcolbes, dpinto}@pol.una.py

Abstract

Elastic Optical Networks (EONs) represent a high-spectral-efficiency paradigm for accommodating heterogeneous traffic demands. However, EONs impose stringent physical-layer operational constraints, including spectrum non-overlapping, contiguity, and continuity, collectively designated as the Routing and Spectrum Assignment (RSA) problem. The integration of adaptive modulation schemes enhances spectral utilization by dynamically allocating resources according to transmission distance and demand characteristics, thereby extending the problem formulation to Routing, Modulation Level, and Spectrum Assignment (RMSA).

In IP-over-EON architectures, the aggregation and grooming of low-bandwidth IP traffic flows are critical for optimal utilization of optical channel capacity. The deployment of Multi-wavelength Sliceable Bandwidth Variable Transponders (MW-SBVTs), which enable simultaneous multi-carrier transmission within bounded spectral tuning windows, introduces additional complexity. This necessitates explicit joint transponder allocation, giving rise to the Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment (RMLSTA) problem.

This work addresses the static RMLSTA problem in IP-over-EON architectures through two complementary methodologies: a sequential multi-phase Integer Linear Programming (ILP) formulation and an efficient Multi-Objective Genetic Algorithm (GA). Given an IP traffic demand matrix and physical network topology, both approaches optimize the resource allocation following a lexicographic multi-objective optimization framework: minimizing the maximum utilized spectrum index, the total number of allocated frequency slots, and the number of active transponders.

The proposed multi-phase ILP formulation decomposes the intractable joint problem into four consecutive optimization stages, solving each subproblem to exact stage-wise mathematical optimality. Extensive numerical simulations demonstrate that the multi-phase ILP achieves superior spectral and transponder utilization at the expense of computational scalability under high traffic loads. Conversely, the proposed GA metaheuristic achieves a favorable and robust trade-off between solution quality and computational efficiency, generating highly competitive resource assignments within predictable execution times.

Keywords: IP-over-EON, RMLSTA, Multi-wavelength Transponders, Integer Linear Programming, Genetic Algorithms

1 Introduction

The telecommunications sector has undergone significant technological transformation, driven by rapid technical innovation, market liberalization, and the ubiquitous expansion of the Internet. This evolution necessitates the continuous advancement of the underlying infrastructure deployed to provision services, which must now accommodate the increasingly stringent requirements of contemporary applications such as multi-media content delivery, cloud computing, and high-capacity backbone networks. The success of the current global technological transformation [1] fundamentally relies on the deployment of robust, high-capacity, and cost-effective network infrastructure. Within this context, optical fiber has emerged as the predominant transmission medium for modern telecommunication systems. In this regard, Wavelength Division Multiplexing (WDM) [2] provides a viable near-term solution for maximizing the bandwidth capacity of optical fiber while requiring minimal modifications to existing network equipment and deployed infrastructure.

In optical fiber networks, WDM represents the predominant technique for establishing connections, enabling data transmission through multiple optical channels within a single physical fiber. However, a significant limitation of conventional WDM-based optical networks is their spectral rigidity. This inherent inflexibility frequently results in suboptimal resource allocation, underutilized capacity, and insufficient adaptability to dynamic service demands.

To overcome the inherent limitations of conventional WDM networks and accommodate the exponentially increasing bandwidth demands [3], Elastic Optical Networks (EONs) represent a promising paradigm. EONs leverage a fine-grained, flexible spectrum allocation mechanism that assigns variable spectral bandwidth to individual channels based on their instantaneous capacity requirements. This adaptive allocation strategy enables dynamic spectral partitioning, thereby achieving improved spectral efficiency compared to fixed-grid approaches [4].

Despite significant advancements in addressing the limitations of WDM architectures, EON technologies present fundamental optimization challenges that must be resolved for practical deployment. The most prominent of these is the Routing and Spectrum Assignment (RSA) problem, which constitutes a critical resource allocation challenge in EON design. The RSA problem is formally defined as the determination of an optimal optical path for each unicast connection request such that the aggregate spectrum utilization across the network is minimized while satisfying all physical layer constraints. An optical path is formally characterized by two essential elements: (a) a contiguous sequence of optical fiber links forming a physical route from the source node to the destination node, and (b) a designated spectral interval consistently allocated across each constituent fiber link along the established route. The concurrent determination and allocation of both the physical routing topology and its corresponding spectral resources constitutes what is formally defined as a lightpath [5].

As depicted in Figure 1, client traffic originates at the upper network layers, specifically the IP layer. The interface between the IP and EON layers is realized through colored router line cards, which facilitate direct inter-layer connectivity via optical-electrical-optical (OEO) conversion mechanisms. To illustrate the multi-layer routing process, consider a representative traffic flow originating at IP node B with destination IP node C. The end-to-end transmission is accomplished through cooperation between network layers: the traffic flow is first mapped from IP node B to EON node 2, subsequently routed through the optical layer via EON node 4, and finally delivered to the destination IP node C, thereby completing the cross-layer forwarding path.

Initially, the network operates in an idle state with no active connection requests. Consider three initial connection requests at the IP layer: AB, AD, and BC. These requests are routed through the IP layer topology, as illustrated in Figure 1 (request AB is depicted in yellow, BC in blue, and AD in red). The traffic demands on these IP virtual links are subsequently mapped to connection requests at the optical layer, with respective bandwidth requirements of $1.0 \times C$ GHz for virtual link AB, $0.8 \times C$ GHz for virtual link AD, and $1.0 \times C$ GHz for virtual link BC. Upon the first service request, traffic is initiated at IP node A and mapped to optical node 1 at the network interface. Within the optical domain, the traffic is then routed from optical node 1 to optical node 2 employing a shortest-path routing algorithm applied to the physical network topology. Concurrently with route computation, the optimal modulation format and the necessary number of spectral slots are determined for the selected lightpath based on distance-adaptive transmission constraints. Subsequently, a contiguous block of spectral slots is identified within the optical spectrum domain, ensuring compliance with all physical layer constraints including spectrum continuity, contiguity, and non-overlapping requirements. Following spectrum allocation, the transponder assignment procedure is executed to establish the optical-electrical interface [6]. Upon completion of both spectral resource allocation and transponder assignment, the traffic flow is delivered from optical node 2 to the destination IP node B, thereby completing the end-to-end lightpath establishment.

The inherent interdependence between IP layer routing decisions and the optical layer RSA problem necessitates a joint optimization framework to achieve efficient utilization of network resources across both

layers. This cross-layer optimization paradigm, wherein IP routing and optical resource allocation are addressed in an integrated manner, is formally referred to as the IP-over-EON problem [7, 8, 9]. Given the computational intractability of the RSA problem, formally classified as NP-complete [10], the development of efficient and scalable solution methodologies constitutes a fundamental research challenge. Existing solution approaches can be categorized into two principal classes: exact methods based on Integer Linear Programming (ILP) formulations, and metaheuristic techniques, including Genetic Algorithms (GAs) [11, 12].

While monolithic ILP-based formulations guarantee theoretical global joint optimality, their extreme combinatorial complexity prevents scalability beyond small network instances. To overcome this computational limitation, decomposed multi-phase ILP approaches partition the problem into sequential stages. While solving each stage to exact mathematical optimality achieves stage-wise optimality rather than guaranteeing the global joint optimum of the monolithic problem, it provides high-quality near-optimal solutions with practical computational tractability. In contrast, metaheuristic approaches such as GAs exhibit superior scalability characteristics and predictable execution times, making them well-suited for large-scale network planning.

EONs provide considerable operational flexibility, particularly through distance-adaptive modulation formats and advanced sliceable transponder assignment schemes. However, these capabilities introduce new design dimensions that expand the traditional RSA problem into several challenging variants:

- (a) *Routing, Modulation Level and Spectrum Assignment* (RMLSA) [13],
- (b) *Routing, Spectrum and Transponder Assignment* (RSTA) [6], and
- (c) *Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment* (RMLSTA).

The RMLSTA problem, especially within the integrated IP-over-EON cross-layer architecture, remains largely unexplored in the existing literature.

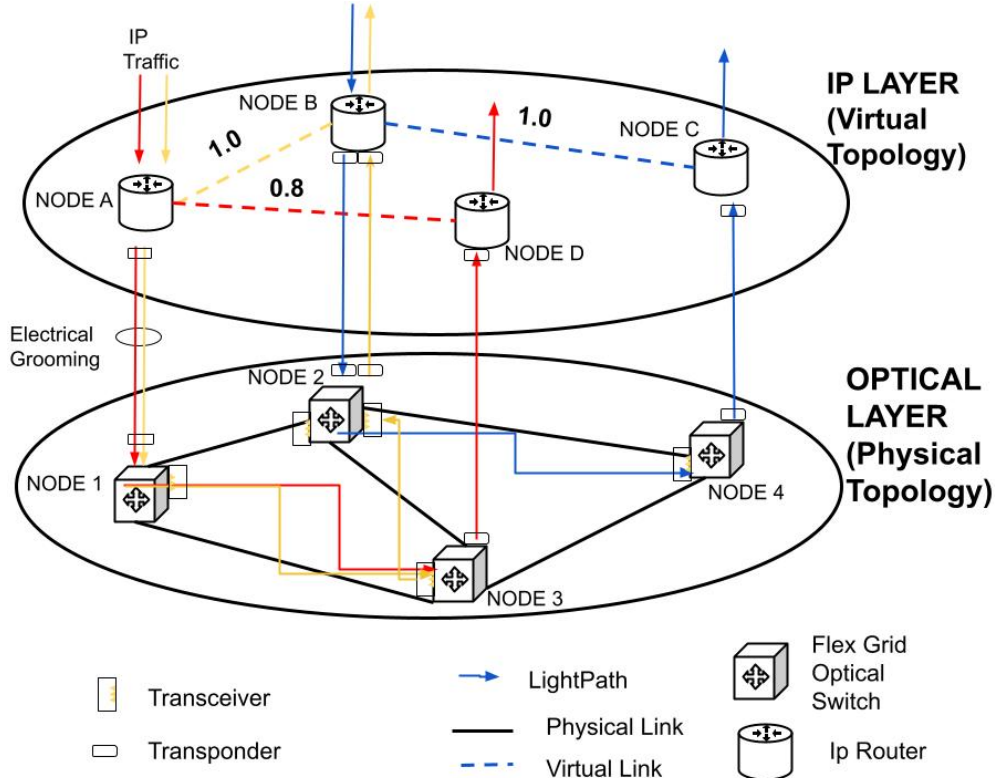


Figure 1: IP-over-EON cross-layer network architecture.

In this context, the principal contributions of this work are summarized as follows:

1. We introduce and formally define the static IP-over-RMLSTA problem, integrating multi-hop IP-layer grooming and routing with physical-layer Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment.

2. We develop a novel multi-phase Integer Linear Programming (ILP) formulation for the IP-over-RMLSTA problem, which extends serial decomposition principles (originally explored for single-layer optical RMLSA) into a four-stage cross-layer framework (IPR $\rightarrow$ RML $\rightarrow$ SA $\rightarrow$ TA), where each stage is solved to exact stage-wise mathematical optimality.
3. We devise an efficient Multi-Objective Genetic Algorithm (GA) specifically tailored to the IP-over-RMLSTA problem, incorporating domain-specific chromosome encoding, dedicated genetic operators, and lexicographical fitness evaluation.
4. We present an extensive computational performance evaluation comparing the multi-phase ILP and GA approaches across three standard SNDlib network topologies (Dfn-bwin, Geant, and Cost266) under varying static traffic loads, supported by rigorous paired statistical significance testing.

The remainder of this article is structured as follows: Section 2 presents the foundational principles of Elastic Optical Networks, including modulation level adaptation and MW-SBVT transponder constraints. Section 3 details IP-over-EON routing and energy-saving grooming principles. Section 4 reviews related literature. Section 5 presents the multi-phase ILP formulation and discusses its optimality properties. Section 6 introduces the proposed Genetic Algorithm. Section 7 analyzes the numerical results and statistical evaluations. Finally, Section 8 concludes the paper and outlines future research directions.

2 Optical Architecture

This section presents the fundamental concepts of Elastic Optical Networks (EONs), including a discussion of the basic optical routing problem, RSA problem constraints, an overview of challenging variants of the RSA problem, and a concise explanation of IP-over-EON routing.

2.1 EON overview

Elastic Optical Networks (EONs) provide a finer granularity of spectral allocation, and are considered a promising alternative to Wavelength Division Multiplexing (WDM) networks [14]. Jinno et al. [4] first presented the method called *Single Slot on the Grid Approach*. In this methodology, the optical spectrum is partitioned into fixed-size slots (12.5 GHz as specified by the ITU-T¹ in the G.694.1 standard) [15] with each optical path assigned a corresponding *central frequency*. When operating within the spectral band C (1530–1565 nm), each CF must be defined as $193.1 + n \times 0.0125$ THz, where n is an integer number and 193.1 THz represents the ITU-T’s anchoring frequency for transmission within the C band. It is also worth mentioning the concept of *slot width* (SW), representing the amount of spectrum allocated to a given request. This quantity is calculated as the product of the individual slot size and the number of slots requested. Then $SW = 12.5 \text{ GHz} \times m$, where m is a positive integer [16].

In addition to the previously described spectrum division, bandwidth allocated to optical paths can be dynamically adjusted, expanding or contracting in response to the traffic volumes, or evolving user requirements. This inherent flexibility, along with the granular spectrum allocation, is the basis for designating this technology as “Elastic” [17].

EON technologies exhibit several characteristics that are worth mentioning:

- Support for high bandwidth requirements, including 400 Gbps, 1 Tbps, and beyond, for data transmission. While fixed-grid networks can accommodate such bandwidths through multiplexing of smaller units (e.g., 100 Gbps or 200 Gbps), this approach leads to faster spectrum depletion compared to employing EONs.
- Variable bandwidth and accommodation of multiple data rates: as previously noted, a single EON can accommodate data rates of 100 Gbps and higher. Consequently, it is logical that the allocated spectrum is dynamically adjusted for each demand based on the specific data rate and transmission distance, rather than inefficiently allocating excessive spectrum to satisfy bandwidth requirements.
- Capability for finer-grained bandwidth allocation using a technique called Nyquist Dense Wavelength Division Multiplexing (DWDM), also known as superchannels.
- Dynamic Network: refers to the capacity of the optical network to adapt and respond quickly to fluctuating bandwidth demands at the client layer. Specifically, the network can adjust its configuration and transmission capacity to meet the specific bandwidth requirements of services or applications being

¹Telecommunication Standardization Sector, from the International Telecommunication Union (ITU)

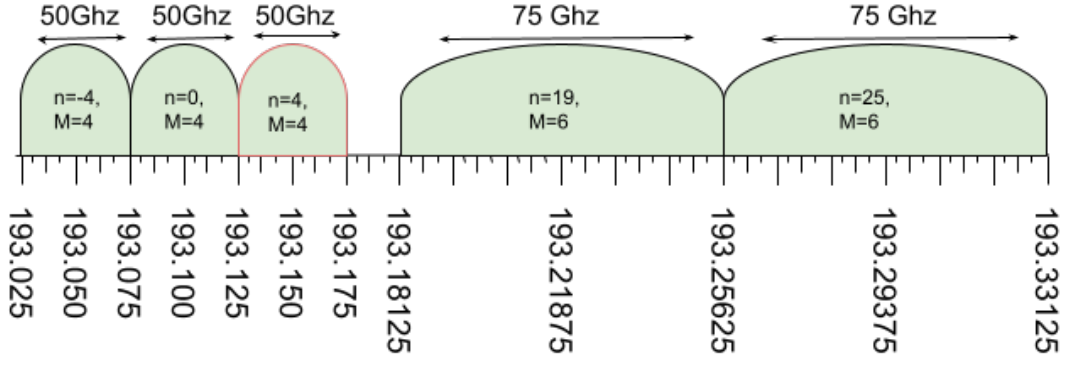


Figure 2: Flexible Grid. Consider this example of channel allocation within an EON, comprising two 50 GHz channels and two 75 GHz channels. The interstitial space between these channel sets could potentially allocate another 50 GHz channel (with $n = 4$ and $m = 4$), leaving 6.25 GHz as guard band. However, this space could be employed more efficiently through the use of smaller channels, such as 25 GHz channels, via flexible grid technology. This contrasts with fixed-grid systems, which can only allocate 50 GHz channels. Flexible grids thus offer improved spectral exploitation due to variable channel bandwidth support.

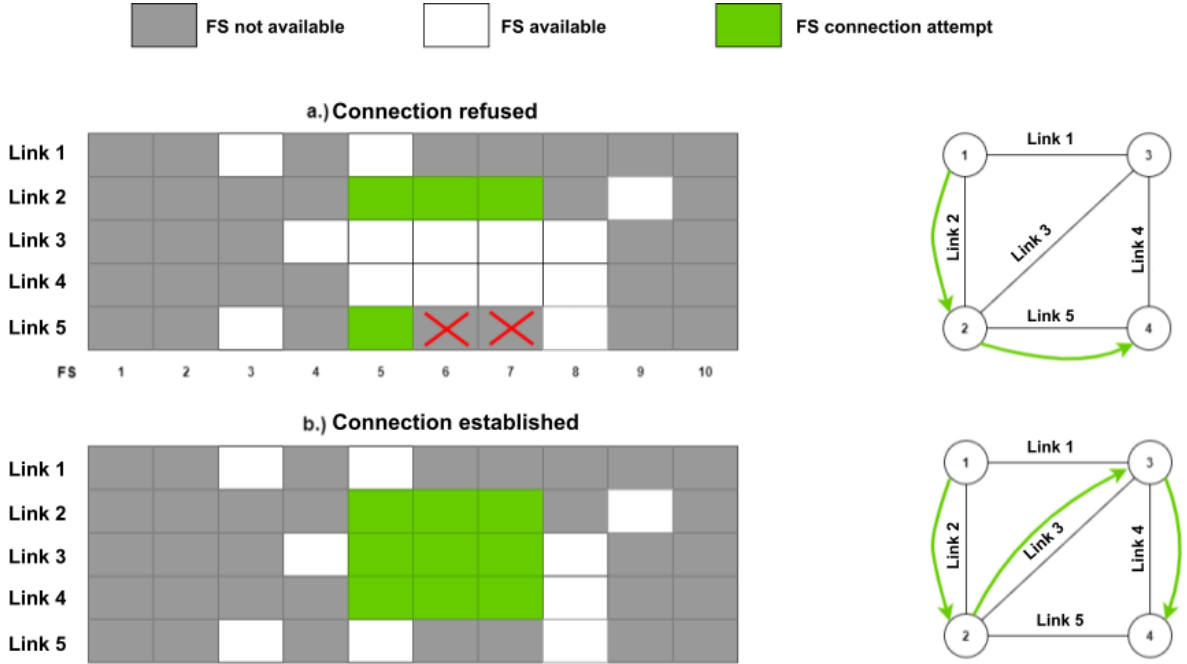


Figure 3: RSA restrictions. A simplified illustrative example involving a request for three spectral slots, originating at node 1 and destined for node 4. Figure (a) depicts a scenario where no optical path satisfies optical layer restrictions, resulting in request rejection. Conversely, Figure (b) illustrates a feasible optical path comprised of links 2, 3, and 4. Along this path, slots 5, 6, and 7 comply with optical layer constraints. In this illustrative example, the inclusion of guard bands between adjacent optical paths has been omitted.

utilized at any given time. A prime example is IP-over-EON traffic, where transponders dynamically adjust their bandwidth in accordance with IP layer demands. This enabling technology is commonly referred to as *bandwidth variable transponders* (BVTs).

EON nodes typically comprise BVTs [5] and *bandwidth variable-wavelength Cross-connects*, (BV-WXCs) as illustrated in Figure 4. The internal structure of a BV-WXC is depicted in Figure 5. Transmitter BVTs perform the conversion of electrical signals to optical signals, with the inverse conversion occurring within the receiver BVT at the destination nodes. It is noteworthy that BVTs can dynamically adjust transmission rates and, where applicable, modulation formats, enabling transmission at low and high data rates. Consequently, for longer transmission distances, more robust, albeit less efficient modulation formats

can be utilized, while shorter distances can allow the use of more spectrally efficient modulations. The BV-WXCs facilitate the switching of light from subcarriers traversing across an optical fiber to a switching node. These subcarriers can effectively switch and send light to an outbound optical fiber without undergoing electrical-to-optical conversion. This functionality allows BV-WXCs to establish end-to-end optical paths from source to destination nodes by switching subcarriers to the appropriate outbound switch port [16].

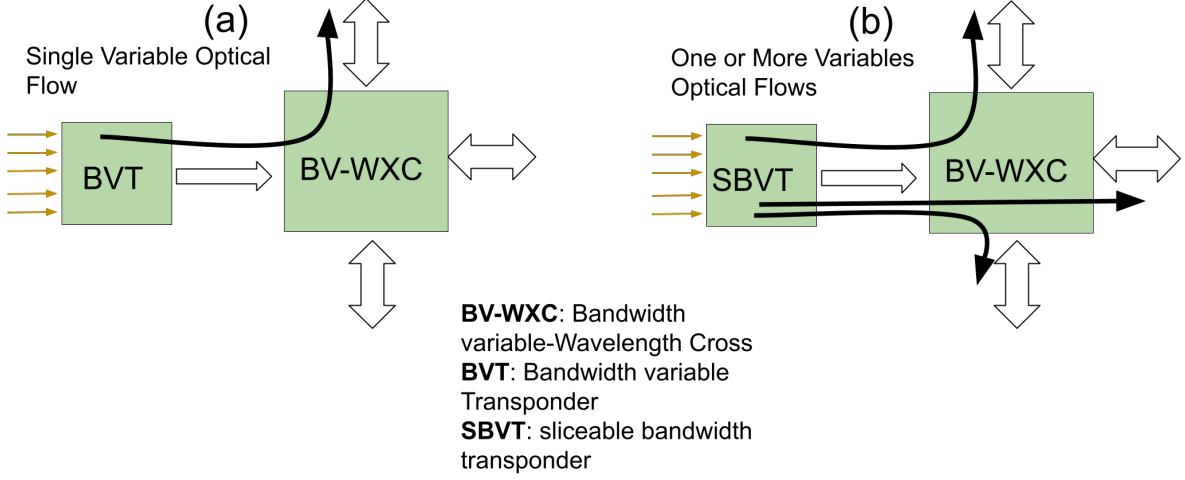


Figure 4: Comparison between BVT and SBVT transponders. SBVTs are capable of generating multiple sub-carriers that can transmit to one or multiple destinations in parallel, or combine into a single high-bandwidth super-channel (*sliceability*). In contrast, with a high-speed BVT, a portion of the bandwidth capacity may be unusable due to optical reach limitations or transmission path impairments.

BV-WXCs facilitate the establishment of optical paths by switching subcarriers to the appropriate output port of the switch. The *Bandwidth Variable Spectrum Selective Switches*, (BV-SSS) enable the capability to add/drop channels for local signals, perform wavelength multiplexing/demultiplexing, and execute optical switching functions. The incoming light from a fiber is separated into its constituent spectral components using a dispersive element (*splitter*), and subsequently each component is directed to a one-dimensional mirror array, which redirects light to the corresponding output fiber [16].

Given the features of the constituent elements within EONs, path computation algorithms can determine optical paths with dynamic bandwidth, thus assigning optimally spectral resources.

2.2 Routing and Spectrum Assignment

The simplest formulation of the RSA problem is based on a single request, defined by a tuple of origin and destination nodes and a required bandwidth [16]. Subsequently, the RSA algorithm searches for a suitable path and a contiguous block of spectral slots for each optical fiber link across that path, such that the available bandwidth satisfies the request and adheres to the following optical layer constraints [5]:

- **Spectral Slot Contiguity (Adjacency):** this constraint mandates that each slot assigned to a given optical path must be contiguous.
- **Spectral Continuity:** This constraint states that each slot assigned to an optical path must be the same for each optical fiber along the path, considering that there are no optical conversion capabilities present within the network.
- **Spectral Conflict Constraint:** This constraint ensures that an assigned spectral slot to one optical path must not be simultaneously assigned to any other optical path in the same fiber link.

Depending on traffic patterns, RSA can be classified as either static or dynamic. In the static case, the set of connection requests is known a priori, and the objective is to compute an optical path for each request while satisfying optical layer constraints and minimizing total spectrum utilization. Conversely, in the dynamic case, connection requests arrive over time and the objective is to calculate optical paths that minimize request blocking [5].

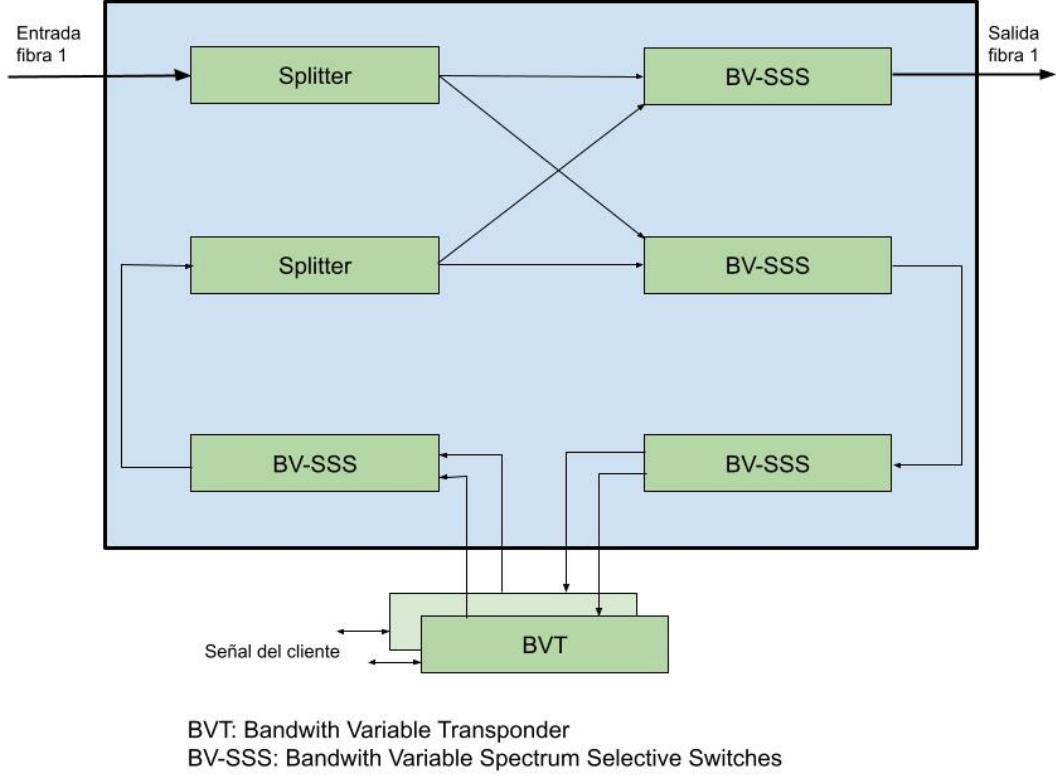


Figure 5: BV-WXC architecture. Implementation example of a *Bandwidth Variable - Cross Connect* (BV-WXC), employing *Bandwidth Variable Spectrum Selective Switches* (BV-SSS) in a broadcast-and-select configuration to provide add/drop functionality for local and transit signals. A BV-SSS performs wavelength multiplexing/demultiplexing and optical switching using integrated spatial optics, Liquid Crystal on Silicon (LCoS), or MEMS technologies to achieve flexible bandwidth and tunable center frequency.

2.3 Modulation level

Modulation is the process of encoding data generated by a source onto a carrier signal of a specific central frequency [2]. The utilization of modulation techniques over optical networks improves spectral usage efficiency, and increases flexibility and fault tolerance [13]. The traditional RSA problem only considers a single modulation scheme for all optical signals. However, improved spectral usage can be achieved by considering multiple modulation formats. In this approach, each incoming request within the network is assigned a specific modulation scheme based on the optical path length. Shorter path lengths make it possible to use more efficient modulation schemes, which reduces the number of required slots to satisfy the requested bandwidth. This process of assigning modulation schemes as a function of the path length is called *Modulation Level Assignment* (MA).

The underlying principle is to assign a modulation scheme that maximizes the data transmission rate, thereby minimizing the number of required slots. Shorter path lengths enable the use of modulation schemes with higher transmission rates [13]. In this work the following modulation formats are considered [18]:

- *Binary Phase Shift Keying* (BPSK) for distances less than $L1 = 2000$ km,
- *Quadrature phase-shift keying* (QPSK) for distances less than $L2 = 1000$ km,
- *8-Quadrature Amplitude Modulation* (8-QAM) for distances less than $L3 = 500$ km.

Each symbol in a modulation scheme carries a specific amount of bits, as illustrated in Figure 6. In the simplest case, BPSK modulation transmits a single bit per symbol, resulting in a spectral efficiency of $R = 1$. QPSK modulation transmits two bits per symbol, yielding an efficiency of $R = 2$. Similarly, 8-QAM has an efficiency of $R = 3$ [19]. These efficiency values can be used to calculate the required number of spectral

slots for each request, based on route distances, according to the following rule:

$$FS = \left\lceil \frac{\lambda}{R \times C} \right\rceil \quad (1)$$

where λ represents the requested bandwidth in GHz, C denotes the spectral width of a single slot using BPSK (conventionally 12.5 GHz), and R refers to the modulation efficiency, expressed as the number of bits per symbol.

Consider as an example a request with a path length of 800 km and a bandwidth requirement of 25 GHz. For this scenario, the optimal modulation scheme is QPSK, and the number of required slots is calculated as $FS = \lceil \frac{25}{2 \times 12.5} \rceil = 1$. Now, consider a second request with a path length of 1200 km and the same 25 GHz bandwidth requirement. For this instance, the optimal modulation scheme is BPSK and the number of slots is $FS = \lceil \frac{25}{1 \times 12.5} \rceil = 2$.

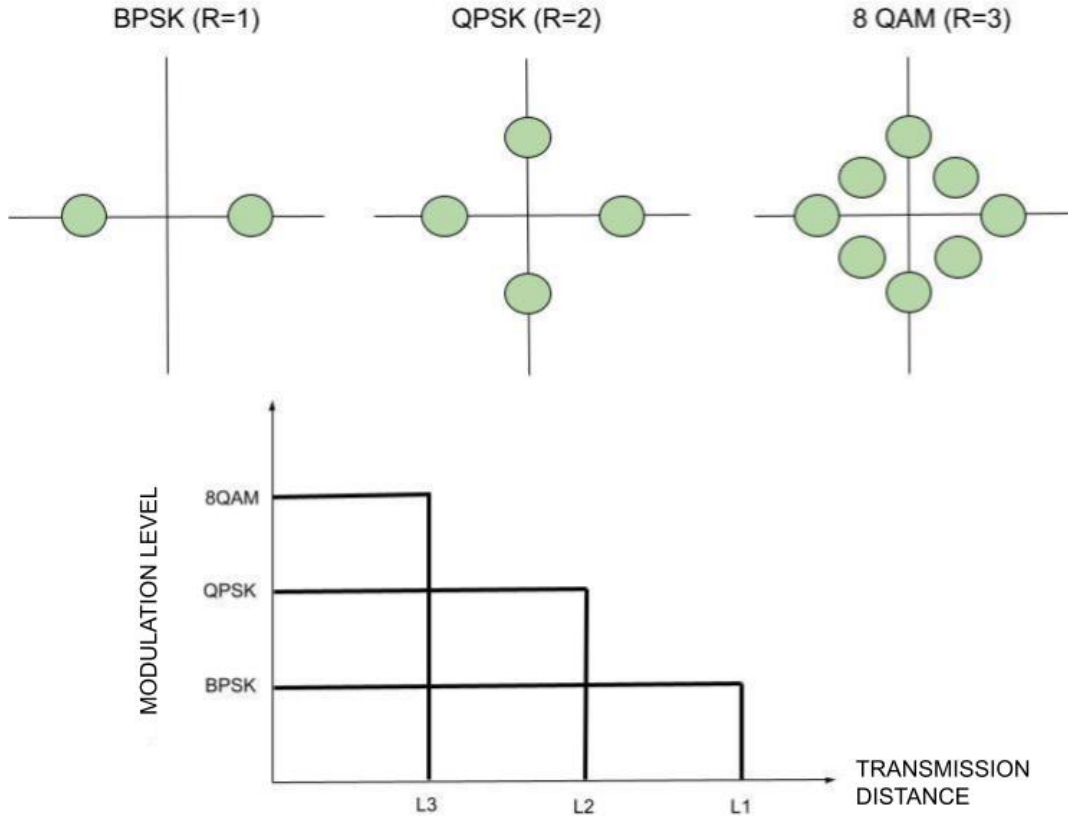


Figure 6: Modulation schemes versus transmission reach. Distance-adaptive modulation improves spectral efficiency by reducing the required frequency slots for shorter transmission paths through higher bits-per-symbol formats. Higher-order schemes (such as 64-QAM) require higher optical signal-to-noise ratios (OSNR) and are suited for shorter reach, whereas robust formats (such as BPSK and QPSK) provide extended reach [4].

2.4 Transponder assignment

Bandwidth Variable Transponders (BVTs) are optoelectronic devices that convert electrical signals, encoding information for transmission across an optical network, into corresponding optical signals. These devices receive data within the electronic domain, perform a conversion, and transmit it in the optical domain. Analogous to a translator, BVTs can adjust bandwidth based on the transmission rate and modulation format employed [20].

For shorter optical paths, BVTs can utilize spectrally efficient modulation formats, such as 8-QAM, to achieve high-speed transmission. Conversely, for longer optical path distances, BVTs can optimize a trade-off between spectral efficiency and robustness by employing lower-order modulation formats when optical path distances are longer, such as QPSK or BPSK. In order to mitigate capacity wastage in BVTs, multi-channel transponders with variable bandwidth were developed, called *Sliceable Bandwidth-Variable Transponders* (SBVTs) [21, 22].

SBVTs typically utilize individual lasers to generate each optical path; that is, the device is composed of multiple lasers (*Multi Laser*, ML), and is called an ML-SBVT. Alternatively, a single laser source generating multiple wavelengths can be employed to generate multiple optical paths, referred to as *Multi Wavelength* (MW), and these devices are called MW-SBVTs. MW-SBVTs offer improved spectral efficiency when using super-channels, due to reduced sub-channel interference. However, MW-SBVTs introduce an additional constraint on spectral assignment within the shared laser beam [6].

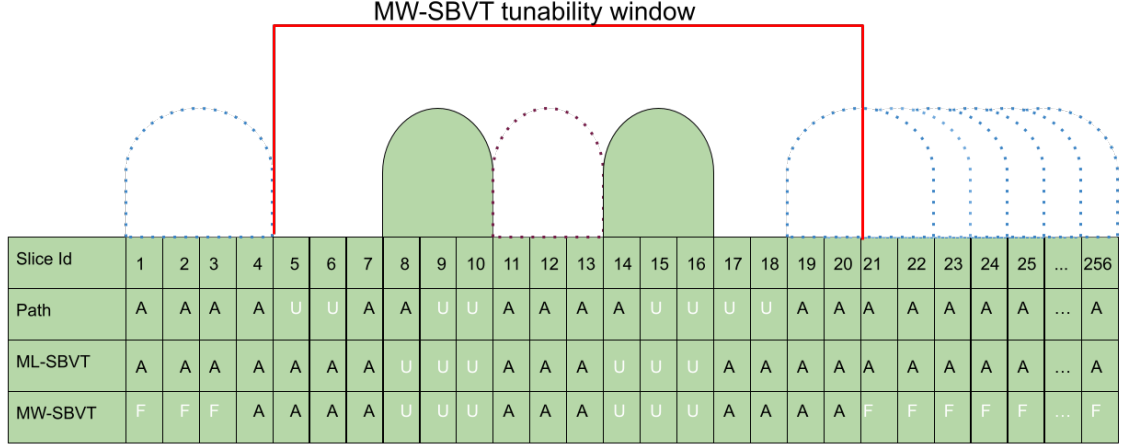


Figure 7: Spectral assignment constraints in MW-SBVTs. Two optical carriers (green) are assigned to slots 8–10 and 14–16. When an incoming 100 Gbps request requires available spectral slots, ML-SBVTs can utilize any block of four contiguous slots (e.g., 1–4 or 19–22). In contrast, MW-SBVTs enforce a 40 GHz tuning window constraint ($FT = 4$ slots), which renders blocks 1–3 and 21–256 unavailable, requiring the allocation to fall within the remaining available slots 11–13 [6].

2.4.1 Advantages/Disadvantages of ML-SBVT

In [6], a series of advantages and disadvantages of ML-SBVT deployment are delineated, as summarized below:

- Sub-carriers suffers of instability by laser interference and between related carriers there might be a considerable impact, thereby higher band guards are needed. This results in reduced spectral efficiency.
- ML-SBVTs offer complete and independent capacity adjustment for each optical carrier.
- The implementation of sliceability yields significant performance benefits.
- Assuming the availability of tunable lasers, each sub-carrier frequency can be adjusted across the entire C band.
- When utilized on super-channel configurations, internal guard bands are required to avoid subcarrier overlap, which results spectral bandwidth overhead.
- Employing C band tunable lasers enables unrestricted spectral assignment within sub-carriers, allowing utilization of any available portion of the available spectral portion.

2.4.2 Advantages/Disadvantages of MW-SBVT

According to [6], the advantages and disadvantages associated with MW-SBVTs are the following:

- Multiple carriers can be generated from a single laser source, via multi-wavelength generation.
- Spectral efficiency in super-channel deployments is enhanced.
- Inter-carrier interference within the super-channels is reduced, effectively enabling the reduction of guard bands between subcarriers.
- Empirical results demonstrate improved efficacy in super-channel creation.

- Simulations indicate that MW-SBVTs exhibit strong potential in scenarios where the entire traffic is composed of high-bitrate super-channels.
- MW-SBVTs impose specific constraints on the RSA problem, due to limitations in the range of allowable values for separation between subcarriers.

In the context of RSA problems involving MW-SBVT technologies, a novel challenge arises. This challenge pertains to the optimization of transponder assignment, specifically the minimization of active MW-SBVT units, which directly impacts operational expenditures [6].

2.5 RMLSTA problem statement

This work aims to study optical routing and optimal modulation scheme assignment, concurrently optimizing spectrum utilization and MW-SBVT transponder allocation. The usage of MW-SBVTs provides substantial enhancements in terms of spectral efficiency within super-channel configurations, by employing single laser sources, which results in inherently synchronized optical carriers. This synchronization enables a significant reduction of inter-carrier guard band margins within super-channels, resulting in optimized spectral efficiency. Nonetheless, this technology introduces constraints related to carrier tunability, specifically a maximum allowable tuning range, which can limit flexibility in spectrum assignment.

Conversely, ML-SBVTs offer improved flexibility through the independent tunability of each optical carrier. This versatility, however, is accompanied by heightened complexity and cost because of the utilization of multiple laser sources. Despite the tunability limitations, MW-SBVTs present a compelling option for optical networks that require spectral efficiency and a reduction in physical transponder count. However, successful deployment must consider meticulous implementation in the assignment of optical routes (RSA), specifically addressing tunability constraints, in order to mitigate potential spectral allocation conflicts, particularly in scenarios where a single carrier of a MW-SBVT is utilized.

In summary, the choice between MW-SBVT and ML-SBVT is contingent upon a trade-off between spectral efficiency, flexibility in spectral assignment, and hardware limitations. MW-SBVTs represent a more cost-effective solution, albeit with certain constraints in tunability. In this study, the selection of MW-SBVTs over ML-SBVTs is primarily justified by the capacity of MW-SBVTs to emulate the functionality of ML-SBVTs through the application of an operational window constraint. This approach enables a reduction in the number of required optical transponders, thereby optimizing costs and infrastructure requirements, albeit with a concomitant limitation in spectral capacity. This methodology proves more efficient and profitable in numerous scenarios, particularly in networks already configured to operate with MW-SBVTs. This problem is designated in this work as the *Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment* (RMLSTA) problem, which, to the best of our knowledge, has not been comprehensively addressed in the existing literature. Figure 8 provides an illustrative example of the RMLSTA problem definition using a representative network topology.

3 IP-over-EON Overview and Concepts

IP traffic between network nodes is transported via optical paths established across the underlying Elastic Optical Network (EON) layer. Following the multi-layer framework proposed by Ríos et al. [23], this study considers multi-segment traffic routing within the IP layer. Under this model, each individual segment of an IP route is treated as an independent routing request to be provisioned in the optical layer.

The client layer consists of IP routers interconnected via virtual (logical) links. These routers generate a set of IP traffic demands. Based on these demands, a virtual topology is constructed, as detailed below. Subsequently, the virtual links in the IP layer are translated into a set of optical connection requests that must be routed and assigned resources in the underlying optical layer using RSA algorithms.

The IP layer interfaces directly with the EON layer through colored router line cards. These line cards provide an electro-optical boundary between IP and EON devices via optical-electrical-optical (OEO) conversion processes, as depicted in Figure 1. IP routers are typically equipped with line cards possessing a standardized transmission capacity of C GHz [24].

3.1 Energy-Saving Routing and Traffic Grooming

To optimize energy consumption and network equipment utilization, this work employs the Dynamic Upper Dynamic Lower (DUDL) resource scalability strategy [24]. This approach enables dynamic coordination and re-routing across both physical and logical layers in response to temporal traffic variations.

An illustrative example of the DUDL traffic grooming mechanism is depicted in Figure 9:

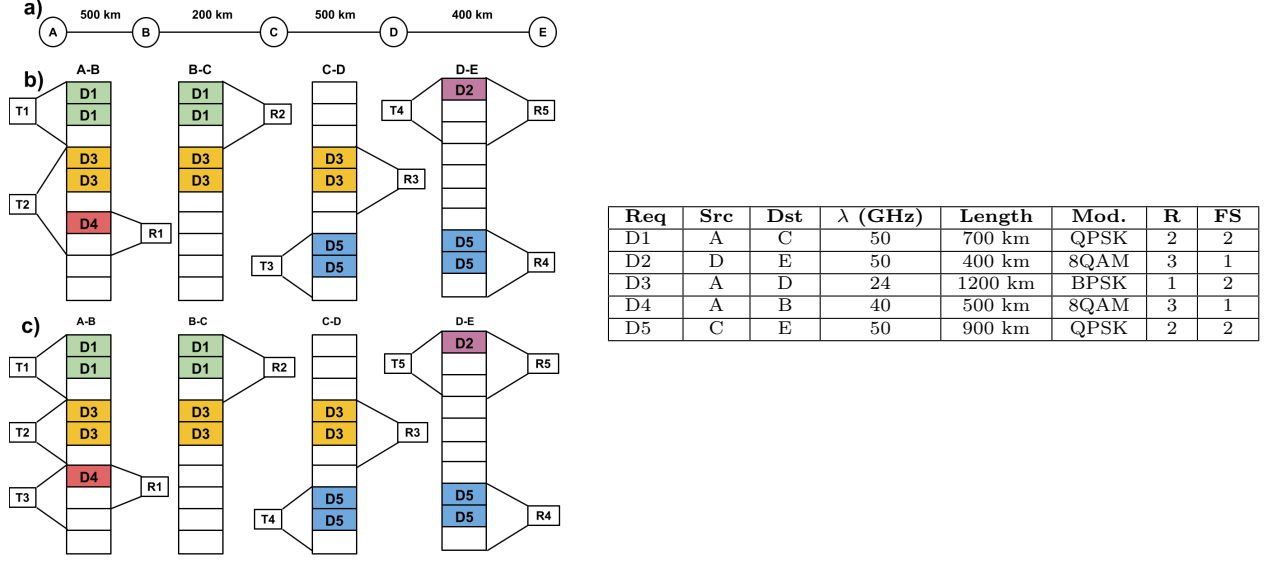


Figure 8: Illustrative RMLSTA allocation comparison between ML-SBVTs and MW-SBVTs: linear 5-node topology with five connection requests (D1–D5), corresponding distance-adaptive modulation levels, and resulting spectrum allocation. While ML-SBVTs require five dedicated lasers (one per request), MW-SBVTs share laser sources across subcarriers within the tuning window FT , reducing active transponders to four while respecting spectral window constraints [6].

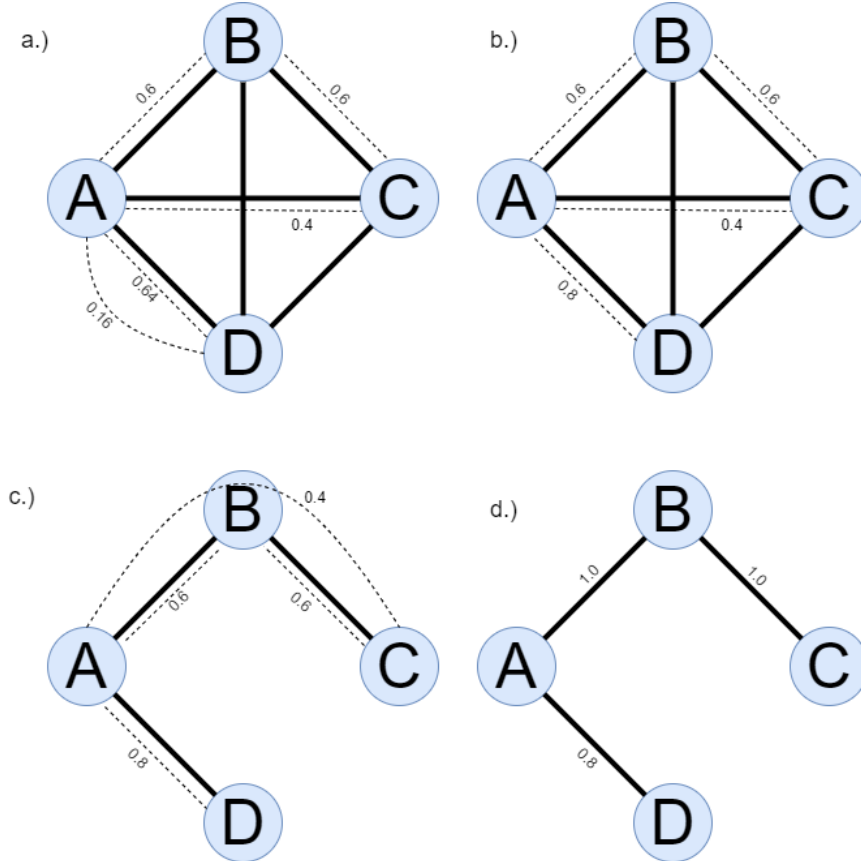


Figure 9: Illustrative example of IP traffic aggregation and energy-efficient routing strategies.

- (a) *Initial IP requests:* Figure 9(a) displays a representative set of traffic demands originating at the IP layer. Each demand is quantified proportionally to the capacity of a spectral slot under base modulation (C GHz), where a value of 1.0 represents a bandwidth demand of C GHz. The set of demands includes flows AB ($0.6 \times C$ GHz), AC ($0.4 \times C$ GHz), AD₁ ($0.64 \times C$ GHz), AD₂ ($0.16 \times C$ GHz), and BC

$(0.6 \times C \text{ GHz})$.

- (b) *Flow aggregation*: Demands AD_1 and AD_2 , sharing identical source (A) and destination (D) nodes, are merged into a single consolidated virtual demand AD with an aggregate load of $0.8 \times C \text{ GHz}$, as shown in Figure 9(b). Virtual link AD is established and utilizes 80% of the line card capacity at both endpoints.
- (c) *Multi-hop grooming*: High-bandwidth requests AB and BC ($0.6 \times C \text{ GHz}$ each) are provisioned directly on dedicated virtual links. For demand AC ($0.4 \times C \text{ GHz}$), the algorithm seeks to groom traffic onto already established, underutilized lightpaths (path A–B–C) rather than deploying additional transponders, as depicted in Figure 9(c).
- (d) *Dedicated path fallback*: If intermediate links lack sufficient residual capacity, a dedicated lightpath A–C is provisioned, as shown in Figure 9(d) [25].

Consider modeling the IP layer as a virtual topology where each pair of IP nodes is logically connected. By re-routing flows over existing underutilized logical links, transponder hardware utilization and overall energy consumption are significantly reduced. However, this introduces an inherent trade-off: minimizing active transponders may increase the path length (hop count) for certain IP demands, which subsequently impacts the optical reach and required modulation format in the physical layer.

3.2 Cross-Layer Request Mapping

When the network transitions from an idle state to serving active connection requests, the demands are handled through an ordered sequence:

1. Connection requests originate at the IP client layer (e.g., AB, AD, BC).
2. IP traffic is mapped to the corresponding ingress optical interface (e.g., Optical Node 1).
3. A physical route across the EON topology is computed using shortest-path or candidate path algorithms.
4. Distance-adaptive transmission determines the optimal modulation level and required frequency slots (α_{qp}).
5. Spectrum assignment algorithms identify an available block of contiguous and continuous slots satisfying non-overlapping constraints.
6. Multi-wavelength sliceable transponders (MW-SBVT) are assigned, adhering to carrier spacing and tuning window limitations [6].
7. Once physical resources are reserved, end-to-end client traffic forwarding is activated.

4 Related Work

Numerous studies in the literature have addressed resource allocation in IP-over-EON networks, focusing on various combinations of routing, modulation, spectrum, and transponder assignment.

Biernacka et al. [26] investigate the IP-over-EON problem, specifically addressing Routing, Modulation Level, and Spectrum Assignment (RMLSA). In their framework, the IP layer employs the OSPF protocol to route IP demands. The study focuses on dynamic bursty traffic under an optical architecture equipped with Bandwidth Variable Transponders (BVTs), proposing a heuristic that minimizes the total bandwidth of blocked requests.

Zhao et al. [27] propose a cross-layer RSA (CL-RSA) algorithm incorporating adaptive modulation. Their approach jointly considers the virtual and physical topologies using a prioritized minimum weight path selection method. The formulation is evaluated under dynamic traffic with BVT transponders, aiming primarily to minimize frequency slot consumption, without addressing transponder assignment constraints.

Biswas et al. [10] focus on minimizing energy consumption by curtailing the usage of high-power hardware. They address static and dynamic IP-over-EON provisioning using Mixed Integer Linear Programming (MILP) and auxiliary graph heuristics, considering networks equipped with Sliceable Bandwidth Variable Transponders (SBVTs).

Building upon auxiliary graph models, Zhang et al. [28] develop a dynamic traffic grooming algorithm incorporating link weights, traffic policies, and spectrum reservation. Using QPSK modulation and BVTs,

their analysis evaluates trade-offs between minimizing established lightpaths, virtual hops, and physical hops (with load balancing), depending on operator criteria.

In [29], Zhao et al. investigate dynamic traffic grooming in Space Division Multiplexing Elastic Optical Networks (SDM-EON) with multi-core fibers. Their auxiliary graph heuristic evaluates multiple policies to minimize request blocking, including electrical aggregation, optical grooming, and SDM core selection with SBVTs.

Tanaka et al. [25] investigate multi-period IP-over-EON reconfiguration under dynamic traffic, proposing iterative heuristics with adaptive bandwidth resizing and modulation level selection to minimize energy consumption in networks with BVTs and SBVTs.

Zhang et al. [30] analyze energy efficiency under dynamic traffic across four transponder architectures: non-sliceable BVTs (NS-BVTs), fully sliceable BVTs (FS-BVTs), and partially sliceable BVTs (PS-BVTs). For each architecture, they develop ILP models and heuristics that minimize energy consumption across router ports, transponders, and optical amplifiers, employing two grooming schemes: Maximum Optical-Layer Grooming (MOLG) and Maximum Electrical-Layer Grooming (MELG).

Tanaka and Hirano [31] present an in-operation network planning method that dynamically provisions lightpaths to absorb temporal and geographical IP traffic fluctuations using BVT transponders.

Yang et al. [6] investigate the joint Routing, Spectrum and Transponder Assignment (RSTA) problem in EONs with intermediate signal regeneration, analyzing the trade-off between spectral efficiency and hardware deployment costs. Similarly, recent works have explored dynamic impairment-aware RMLSA [18, 4] and multi-core multicast assignment [32].

As summarized in Table 1, existing works address subsets of the cross-layer optimization space (such as RSA, RMSA, or RSTA). However, the comprehensive joint integration of multi-hop IP grooming with physical-layer Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment—which we designate as the Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment (RMLSTA) problem—has not been previously addressed in an integrated framework.

Table 1: Summary of related works on IP-over-EON resource allocation.

Ref.	IP Routing Algorithm	Physical Routing Algorithm	Traffic Type	Transponder Type	Objective Function
[26]	Heuristic OSPF-based IP flow allocation	Most Spectral Efficiency with Longest Spectral Frequency (MSEwLSF)	Dynamic (bursty)	BVT	Minimize total blocked bandwidth in IP-over-EON.
[27]	Cross-layer RSA (CL-RSA) joint virtual/physical topology optimization with adaptive modulation		Dynamic	BVT	Minimize total frequency slots utilized and setup latency.
[25]	Multi-period iterative heuristic reconfiguration with adaptive bandwidth resizing and modulation		Dynamic	BVT, SBVT	Minimize total network energy consumption.
[30]	ILP models and heuristics using MOLG and MELG grooming schemes	Simplified optical routing without RSA constraints	Static	NS-BVT, PS-BVT, FS-BVT	Minimize power consumption of router ports, transponders, and amplifiers.
[28]	Auxiliary graph dynamic grooming heuristic	Spectrum-reserved shortest path	Dynamic	BVT	Multi-objective evaluation: minimize lightpaths, virtual hops, and physical hops, depending on operator criteria.
[33]	Multi-cost IPR+ML+RSA algorithm with cost vector scalarization		Static	BVT, Fixed transponders	Minimize capital and operational network costs.
[31]	In-operation planning under dynamic traffic shifts	Standard RSA	Dynamic	BVT	Minimize optical provisioning operations under fluctuating traffic.
[29]	Auxiliary graph grooming heuristic with K-shortest paths and First-Fit		Dynamic	SBVT	Minimize blocking via electrical, optical, and SDM aggregation.
This work	ILP (DUDL grooming) and Multi-Objective GA	Sequential exact ILP (RML, SA, TA) and GA metaheuristic	Static	MW-SBVT	Lexicographic multi-objective: minimize max slot index (f_1), total slots (f_2), and transponders (f_3).

5 Mathematical Formulation of the IP-over-RMLSTA Problem

This section presents the mathematical formulation developed for the static IP-over-RMLSTA problem. Due to the high combinatorial complexity of jointly optimizing multi-layer routing, modulation adaptation, contiguous spectrum slot assignment, and hardware transponder binding, we propose a multi-phase Integer Linear Programming (ILP) framework that decomposes the problem into four consecutive optimization stages:

1. **IP Routing (IPR) phase:** Computes the optimal virtual topology and multi-hop traffic grooming in the client IP layer, minimizing active logical links.
2. **Routing and Modulation Level (RML) phase:** Computes the physical lightpath routes and distance-adaptive modulation schemes across the optical network, minimizing the maximum per-link spectral load.
3. **Spectrum Assignment (SA) phase:** Allocates contiguous, continuous, and non-overlapping spectral slot blocks to all lightpaths, minimizing the maximum utilized slot index.
4. **Transponder Assignment (TA) phase:** Assigns lightpaths to Multi-wavelength Sliceable Bandwidth Variable Transponders (MW-SBVTs) at each node, enforcing carrier limits and tuning window constraints to minimize the total number of deployed transponders.

These four phases are detailed in the subsequent subsections. To provide a comprehensive formulation, the constants, indices, and variables utilized in the mathematical models are presented in Tables 2, 3, 4, and 5, respectively. In accordance with publication standards, all table captions are placed above the respective tables.

Table 2: IP-over-RMLSTA model constants

Symbol	Description
$ \cdot $	Set cardinality
V_{ip}	Set of nodes in the IP layer
E_{ip}	Set of links in the IP layer network
$\mathcal{R}$	Set of traffic requests in the IP layer
C	Frequency slot bandwidth (in GHz, base 12.5 GHz)
SR	Total number of requests in the IP layer ($ \mathcal{R} $)
ω_r	Bandwidth required by request $r \in \mathcal{R}$ in the IP layer (in Gbps)
s_r	Source node of request $r \in \mathcal{R}$ in the IP layer
d_r	Destination node of request $r \in \mathcal{R}$ in the IP layer
V_{eon}	Set of nodes in the optical layer
E_{eon}	Set of links in the optical layer
$\mathcal{Q}$	Set of requests in the optical layer
K	Number of candidate paths for each request in the optical layer
GB	Number of guard band slots
α_q	Number of slots assigned to request q at maximum spectral efficiency, $\alpha_q = \lceil \frac{\lambda_q}{R \cdot C} \rceil$
α_{qp}	Number of slots assigned to request q on path p , $\alpha_{qp} = \lceil \frac{\lambda_q}{R_p \cdot C} \rceil$
P_q	Set of K candidate paths for request q , $P_q = \{p_{q1}, \dots, p_{qK}\}$
F_{total}	Total number of spectral slots available per optical fiber
FT	Tuning window size (in slots) supported by a transponder
T	Number of transponders available at a node
NL	Maximum number of subcarriers per transponder
M	Large positive constant used in the ILP formulations
$\Omega_{qq'}$	Binary parameter; 1 if the routes of requests q and q' share at least one link, 0 otherwise

5.1 Formulation of IP Routing Model (IPR phase)

The IPR phase routes traffic over the virtual IP layer in order to minimize resource utilization on logical links. To this end, an Integer Linear Programming (ILP) model based on the Dynamic Upper, Dynamic Lower (DUDL) approach is employed.

The algorithm receives as input a virtual network graph (assumed to be fully connected) and the traffic request matrix, where each request r is defined by a source node s_r , a destination node d_r , and a required

Table 3: IP-over-RMLSTA model indices

Index	Description
h, i, j, k	Network node indices used in both virtual and physical layers
r	Traffic request index in the IP layer
q	Traffic request index in the optical layer
R	Modulation level index, where $R \in \{1, 2, 3\}$
(i, j)	Link indices in the virtual or physical layer
t	Transponder index
c	Subcarrier index of a transponder

Table 4: IP-over-RMLSTA decision variables

Variable	Description
$Y_{ijr} \in \{0, 1\}$	Binary variable equal to 1 if logical link (i, j) in the IP layer is used by request r , and 0 otherwise.
$x_{qp} \in \{0, 1\}$	Binary variable equal to 1 if candidate lightpath p is assigned to request q , and 0 otherwise.
$m_{qp} \in \{0, 1\}$	Binary variable equal to 1 if request q on path p uses modulation level m , and 0 otherwise.
$f_q \geq 0$	Integer variable denoting the starting frequency slot index assigned to request q . f_q is relative to f_{OFDM} .
$u_{ijs} \in \{0, 1\}$	Binary variable equal to 1 if frequency slot s on physical link (i, j) is utilized, and 0 otherwise.
C_{IPR}	Total number of frequency slots utilized in the IPR phase.
S_{ij}	Number of slots utilized on logical link (i, j) during the IPR phase.
C_{RML}	Total number of slots utilized in the RML phase.
$X_{qp} \in \{0, 1\}$	Binary variable equal to 1 if path p is utilized by request q , and 0 otherwise.
$F_{ij} \geq 0$	Integer variable representing the total number of spectral slots utilized by link (i, j) in the RML phase.
$C_{SA} \geq 0$	Total number of slots utilized in the SA phase (maximum slot index).
$\delta_{q,q'} \in \{0, 1\}$	Binary variable equal to 1 if $f_{q'} > f_q$, and 0 otherwise.
$z_{qt} \in \{0, 1\}$	Binary variable equal to 1 if request q is assigned to transponder t , and 0 otherwise.
$Z_t \in \{0, 1\}$	Binary variable equal to 1 if transponder t is active, and 0 otherwise.
$C_{TA} \geq 0$	Number of active transponders at optical node $i \in V_{\text{con}}$.
$C_{TS} \geq 0$	Total number of active transponders in the optical network.

bandwidth ω_r . The ILP model seeks the optimal routing that minimizes the aggregate number of logical channels, each dimensioned with the spectral granularity of a frequency slot under base QPSK modulation. Consequently, a reduction in the number of necessary transponders for routing is achieved. The active links resulting from this phase are used to construct the request matrix for the subsequent phase, which operates in the physical layer.

The mathematical formulation for the virtual routing in this first phase is defined as follows:

Objective Function:

$$\text{Minimize } C_{IPR} = \sum_{(i,j) \in E_{ip}} S_{ij} \quad (2)$$

Subject to:

$$C \times S_{ij} \geq \sum_{r \in \mathcal{R}} Y_{ijr} \times \omega_r, \quad \forall (i, j) \in E_{ip} \quad (3)$$

$$\sum_{j \in V_{ip}} Y_{hjr} - \sum_{i \in V_{ip}} Y_{ihr} = \begin{cases} 1, & \text{if } h = s_r, \quad \forall r \in \mathcal{R} \\ -1, & \text{if } h = d_r, \quad \forall r \in \mathcal{R} \\ 0, & \text{if } h \neq s_r, h \neq d_r, \quad \forall r \in \mathcal{R} \end{cases} \quad (4)$$

Equation (2) represents the objective function, formulated to minimize the aggregate frequency slot usage across all links in the IP layer. Equation (3) governs the capacity utilization of link (i, j) : it mandates that the provisioned bandwidth must meet or exceed the traffic flow on link (i, j) , accounting for the spectral granularity C . Equation (4) enforces flow conservation for each traffic request r in the virtual IP layer, ensuring that traffic originates at s_r , terminates at d_r , and is conserved at intermediate nodes.

The output of this optimization phase establishes the active virtual topology and the corresponding capacity allocations. Each active virtual link (i, j) possessing bandwidth S_{ij} is converted into an optical

request q in the optical layer. The request q is characterized by the tuple (v, v', S_{ij}) , where $v, v' \in V_{eon}$ denote the optical nodes mapped from the IP router nodes $i, j \in V_{ip}$.

5.2 Formulation of the Routing and Modulation Level Assignment (RML) phase

This phase comprises three distinct stages. The first two serve as pre-processing steps for the optical layer routing problem, whereas the third presents the formulation of the optimization model. In the first stage, the feasible modulation format for each candidate lightpath is determined based on the path length and optical reach limits. Subsequently, in the second stage, the number of spectral slots (α_{qp}) required for each candidate path p of request q is calculated as a function of the requested bandwidth and the assigned modulation level:

$$\alpha_{qp} = \left\lceil \frac{\lambda_q}{R_p \cdot C} \right\rceil \quad (5)$$

where $\lambda_q = S_{ij} \cdot C$ is the bandwidth of the corresponding logical link, R_p is the modulation efficiency factor (bits/symbol) of candidate path p , and C is the slot bandwidth (12.5 GHz). These slot values serve as input parameters for the mathematical formulation.

The third stage details the formulation of an ILP model for the optical routing problem. The input parameters include the optical network topology, the available spectral slots per link, K candidate routes for each request, and the pre-computed α_{qp} values. The objective is to select a single path for each request, minimizing the maximum per-link spectral load C_{RML} . Notably, the resulting value is a lower bound on the subsequent maximum slot index, as the spectrum non-overlapping constraint is enforced in the SA phase.

The ILP formulation, derived from Ríos et al. [23] and tailored for the multi-phase framework, is defined as follows:

Objective function:

$$\text{Minimize } C_{RML} \quad (6)$$

Subject to:

$$C_{RML} \geq F_{ij}, \quad \forall (i, j) \in E_{eon} \quad (7)$$

$$F_{ij} = \sum_{q \in \mathcal{Q}} \sum_{\{p \in P_q | (i, j) \in p\}} \alpha_{qp} \times X_{qp} + GB, \quad \forall (i, j) \in E_{eon} \quad (8)$$

$$\sum_{p \in P_q} X_{qp} = 1, \quad \forall q \in \mathcal{Q} \quad (9)$$

Equation (6) defines the objective function, which minimizes the maximum spectral usage (C_{RML}) across the optical network. Constraint (7) ensures that C_{RML} bounds the utilized capacity for each link (i, j) , designating C_{RML} as the maximum number of slots on the most congested link. Equation (8) computes the specific load for each link by aggregating the spectral slots of all requests traversing that link along with the required guard band GB . Finally, Equation (9) enforces the single-path routing constraint, guaranteeing that each demand q is served by exactly one route from its candidate set P_q . The resulting path assignments and slot allocations serve as inputs for the next phase.

5.3 Formulation of the Spectrum Assignment Model (SA) phase

This phase addresses the Spectrum Assignment (SA) problem, with the objective of determining the frequency slot allocation for each request $q \in \mathcal{Q}$. The model is designed to allocate a contiguous block of slots while minimizing the maximum slot index utilized across the network (C_{SA}). This allocation must strictly comply with the three fundamental constraints of EONs:

1. **Non-overlapping Constraint:** Two distinct lightpaths traversing a common physical link must be assigned mutually disjoint sets of spectral slots.
2. **Continuity Constraint:** A lightpath must utilize the exact same subset of spectral slots along all physical links constituting its end-to-end route.
3. **Contiguity Constraint:** The frequency slots allocated to a single lightpath must form a consecutive block of spectral indices without spectral fragmentation.

The SA phase comprises two stages. The first stage is a pre-processing step to determine the conflict matrix $\Omega_{qq'}$, a binary parameter indicating whether the lightpaths assigned to requests q and q' share at least one physical link ($\Omega_{qq'} = 1$). If $\Omega_{qq'} = 1$, a spectrum conflict exists, necessitating the enforcement of non-overlapping constraints. In the second stage, the ILP model executes the optimal spectral slot allocation:

Objective function:

$$\text{Minimize } C_{SA} \quad (10)$$

Subject to:

$$C_{SA} \geq f_q + \alpha_q, \quad \forall q \in \mathcal{Q} \quad (11)$$

$$\delta_{qq'} + \delta_{q'q} = 1, \quad \forall (q, q') \in \mathcal{Q} \times \mathcal{Q} : \Omega_{qq'} = 1, q < q' \quad (12)$$

$$f_{q'} - f_q < F_{total} \times \delta_{qq'}, \quad \forall (q, q') : \Omega_{qq'} = 1 \quad (13)$$

$$f_q - f_{q'} < F_{total} \times \delta_{q'q}, \quad \forall (q, q') : \Omega_{qq'} = 1 \quad (14)$$

$$f_q + \alpha_q + GB - f_{q'} \leq (F_{total} + GB) \times (1 - \delta_{qq'}), \quad \forall (q, q') : \Omega_{qq'} = 1 \quad (15)$$

$$f_{q'} + \alpha_{q'} + GB - f_q \leq (F_{total} + GB) \times (1 - \delta_{q'q}), \quad \forall (q, q') : \Omega_{qq'} = 1 \quad (16)$$

Equation (10) formulates the objective function, which minimizes C_{SA} , representing the highest slot index utilized across the network. Equation (11) defines C_{SA} as the upper bound of the allocated spectrum, ensuring it is greater than or equal to the terminating slot index of every request q (starting slot f_q plus spectral width α_q).

Regarding interference constraints, Equations (12)–(14) establish the relative ordering of starting slots for any pair of conflicting requests. Finally, Equations (15) and (16) enforce non-overlapping constraints: they ensure that spectral slot blocks of conflicting requests remain disjoint and separated by a guard band GB .

5.4 Transponder Assignment Model Formulation (TA) phase

The final phase of the framework addresses the Transponder Assignment (TA) problem. Leveraging spectral allocations determined in the previous phase, the objective is to minimize the total number of MW-SBVTs required across the network. Since the transponder assignment for a given node is independent of other nodes, the global problem can be decomposed and addressed separately for each network node.

Table 5: Decision variables for the Transponder Assignment Model

Variable	Description
$z_t \in \{0, 1\}$	Binary variable: 1 if transponder t is activated, and 0 otherwise.
$z_{qt} \in \{0, 1\}$	Binary variable: 1 if request q is assigned to transponder t , and 0 otherwise.
$C_{TA} \geq 0$	Number of active transponders deployed at the evaluated node.
$C_{TS} \geq 0$	Integer variable representing the total number of transponders deployed across the entire network.

The following set of equations defines the ILP model for the TA phase executed at node $v \in V_{con}$:

Objective function:

$$\text{Minimize } C_{TA} = \sum_{t=1}^T z_t \quad (17)$$

Subject to:

$$z_{qt} + z_{q't} \leq 1, \quad \forall (q, q') \in \mathcal{Q}_v : \Omega_{qq'} = 1, \forall t \in \{1, \dots, T\} \quad (18)$$

$$z_{qt} \times (f_q + \alpha_q) - z_{q't} \times (f_{q'} + 1) \leq FT + M \times (2 - z_{qt} - z_{q't}), \quad \forall q, q' \in \mathcal{Q}_v, \forall t \in \{1, \dots, T\} \quad (19)$$

$$\sum_{q \in \mathcal{Q}_v} z_{qt} \leq NL \times z_t, \quad \forall t \in \{1, \dots, T\} \quad (20)$$

$$\sum_{t=1}^T z_{qt} = 1, \quad \forall q \in \mathcal{Q}_v \quad (21)$$

Equation (17) defines the objective function, which minimizes the total count of active transponders C_{TA} for node v . Constraint (18) prevents two lightpaths with overlapping spectrum on any link from sharing the same transponder. Constraint (19) enforces the MW-SBVT spectral window limit: the maximum spectral separation between any two optical carriers generated by transponder t cannot exceed the device tuning range FT . Constraint (20) bounds the maximum number of subcarriers (NL) that can be accommodated by transponder t and ensures that subcarriers are only allocated to active transponders ($z_t = 1$). Finally, Equation (21) mandates that every lightpath $q \in \mathcal{Q}_v$ incident to node v is assigned to exactly one transponder.

Because this model is executed independently for each network node, the total network-wide transponder count C_{TS} is computed as:

$$C_{TS} = \sum_{v \in V_{eon}} C_{TA}(v) \quad (22)$$

5.5 Optimality Properties and Complexity Analysis of the Multi-Phase ILP Approach

A fundamental theoretical question in multi-stage optimization frameworks concerns the relationship between decoupled stage-wise optimality and global joint optimality. In this subsection, we explicitly clarify the optimality properties and mathematical guarantees of the proposed multi-phase formulation.

5.5.1 Theoretical Complexity of the Joint Monolithic Problem

The comprehensive joint IP-over-RMLSTA problem is strictly NP-hard. It subsumes several known intractable combinatorial problems:

- **Virtual Topology Design and Grooming (VTDG):** Optimizing the mapping of arbitrary client-layer traffic demands onto virtual links with multi-hop grooming is known to be NP-hard.
- **Routing, Modulation Level, and Spectrum Assignment (RMLSA):** Even in a single physical layer, RMLSA generalizes the Routing and Spectrum Allocation (RSA) problem, which is equivalent to a constrained path formulation of the NP-complete interval graph coloring problem.
- **Transponder Assignment with Tuning Constraints (TA):** Grouping optical carriers into MW-SBVTs under carrier capacity (NL) and spectral window (FT) constraints constitutes an NP-hard Bin Packing Problem with Conflict Graphs and Range Constraints (BP-C-RC).

In a hypothetical monolithic formulation, cross-layer coupling variables would require high-order non-linear formulations or extensive big- M linearizations that couple client routing (Y_{ijr}), physical path selections (x_{qp}), modulation formats (m_{qp}), slot indices (f_q), and transponder assignments (z_{qt}). For realistic topologies (e.g., Geant with 22 nodes or Cost266 with 37 nodes) and moderate traffic volumes (100–500 requests), such a monolithic model generates millions of binary variables and constraints, rendering it computationally intractable for exact mathematical solvers such as CPLEX.

5.5.2 Stage-Wise Optimality vs. Global Joint Optimality

To overcome computational intractability, our framework decomposes the complete optimization challenge into four sequential stages:

$$\mathcal{P}_{IPR} \longrightarrow \mathcal{P}_{RML} \longrightarrow \mathcal{P}_{SA} \longrightarrow \mathcal{P}_{TA}$$

The mathematical properties of this decomposition are characterized as follows:

1. **Stage-wise (Phase-wise) Exact Optimality:** Each subproblem $\mathcal{P}_k$ ($k \in \{IPR, RML, SA, TA\}$) is formulated as an exact Integer Linear Program and solved to mathematical optimality within its designated operational stage, conditioned on the fixed output decisions $\mathbf{x}_1^*, \dots, \mathbf{x}_{k-1}^*$ yielded by preceding stages.
2. **Absence of Global Joint Optimality Guarantee:** Solving each stage independently to mathematical optimality does *not* guarantee the global joint optimum of the monolithic IP-over-RMLSTA problem. Formally, let Ω_{joint} denote the feasible search space of the monolithic problem, and let $\Omega_k(\mathbf{x}_{k-1}^*)$ denote the feasible region of stage k restricted by the optimal decision $\mathbf{x}_{k-1}^*$ of stage $k-1$. Because $\Omega_k(\mathbf{x}_{k-1}^*) \subset \Omega_{\text{joint}}$, fixing decisions at stage $k-1$ may prune regions of the solution space

containing the globally superior joint trade-off for subsequent stages. For instance, the IPR phase minimizes logical links based on client traffic loads; however, a logical topology that is optimal for IP grooming may force optical demands onto physical paths that suffer from high spectral fragmentation in the SA phase or sub-optimal carrier grouping in the TA phase.

3. **Pragmatic Near-Optimality and Benchmark Utility:** While the sequential multi-phase ILP formulation does not provide a theoretical guarantee of global joint optimality, empirical results demonstrate that it yields high-quality, near-optimal solutions that consistently outperform metaheuristic solutions in terms of resource utilization. Consequently, it serves as a rigorous, computationally viable exact benchmark against which heuristic and evolutionary approaches can be objectively evaluated.

6 Proposed Genetic Algorithm Solution for the RMLSTA Problem

This study proposes a scalable metaheuristic solution for the RMLSTA problem in the optical layer based on a Genetic Algorithm (GA). The overall optimization framework begins with the IP Routing (IPR) phase, which is solved using the ILP formulation presented in Section 5.1. This initial step generates the set of optical traffic requests $\mathcal{Q}$ that serves as input for the GA. Subsequently, the GA processes these requests to compute the joint Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment (RMLSTA). The following subsections describe the fundamental concepts, chromosome representation, genetic operators, fitness evaluation, and an illustrative case study.

6.1 Fundamental Concepts of Genetic Algorithms

Genetic Algorithms (GAs) are population-based metaheuristics inspired by the principles of natural selection and biological evolution [34]. A GA evolves a population of individuals (candidate solutions) through iterative cycles of selection, crossover (recombination), and mutation. By combining high-quality genetic material from parents and introducing stochastic diversity, GAs efficiently explore complex, high-dimensional solution spaces [35].

Our proposed GA formulation follows the multi-objective evolutionary optimization paradigm originally established by Fonseca and Fleming [36]. In this formulation, candidate solutions are evaluated against multiple conflicting network objectives, balancing spectral efficiency and hardware deployment costs.

Algorithm 1 outlines the main workflow of the proposed Genetic Algorithm. The process begins with the generation of an initial population P_0 of size N_{pop} (Line 1). Each individual represents a complete candidate assignment of optical routes, modulation levels, frequency slot blocks, and MW-SBVT transponders.

The population is evaluated using Algorithm 2 (Line 2), and the global best individual $s_{\text{best global}}$ is recorded (Line 3). In each evolutionary generation, the algorithm applies:

- **Selection:** Binary tournament selection randomly samples two candidate individuals and selects the superior candidate based on a lexicographical comparison of the objective vector (f_1, f_2, f_3) (Line 7). This operator is executed twice to select two parent individuals.
- **Crossover:** With crossover probability p_c , a two-point crossover operator recombines the genetic material of the two selected parents to produce two offspring (Line 8).
- **Mutation:** With chromosome mutation probability p_m , the offspring undergo gene-level mutation with probability p_g , introducing stochastic diversity into route assignments (Line 9).

The newly generated offspring population P_{mutation} is evaluated using Algorithm 2 (Line 10). Next, an elitist population replacement strategy merges the current population P_t and the offspring population P_{mutation} into a combined pool of size $2N_{pop}$, sorts all individuals lexicographically by (f_1, f_2, f_3) , and retains the top N_{pop} individuals for the next generation P_{t+1} (Line 11).

The evolutionary search terminates when either:

1. The maximum number of generations G_{max} is reached ($gen \geq G_{max}$), or
2. The best solution has shown no improvement for G_{stall} consecutive generations ($gen_{\text{stalled}} \geq G_{stall}$), indicating convergence.

Upon termination, the algorithm returns the best global solution $s_{\text{best global}}$ (Line 22).

Algorithm 1 Multi-Objective Genetic Algorithm for IP-over-RMLSTA

Require: Population size N_{pop} , Crossover probability p_c , Chromosome mutation probability p_m , Maximum generations G_{max} , Maximum stagnant generations G_{stall} .

```
1:  $P_t \leftarrow \text{GenerateInitialPopulation}(N_{pop})$ 
2:  $\text{EvaluatePopulation}(P_t)$  ▷ Algorithm 2
3:  $s_{\text{best global}} \leftarrow \text{GetBestIndividual}(P_t)$ 
4:  $gen \leftarrow 0$ 
5:  $gen_{\text{stalled}} \leftarrow 0$ 
6: while ( $gen < G_{max}$ ) and ( $gen_{\text{stalled}} < G_{stall}$ ) do
7:    $P_{\text{parents}} \leftarrow \text{Selection}(P_t)$ 
8:    $P_{\text{crossover}} \leftarrow \text{Crossover}(P_{\text{parents}}, p_c)$ 
9:    $P_{\text{mutation}} \leftarrow \text{Mutation}(P_{\text{crossover}}, p_m)$ 
10:   $\text{EvaluatePopulation}(P_{\text{mutation}})$  ▷ Algorithm 2
11:   $P_{\text{new}} \leftarrow \text{ElitistPopulationReplacement}(P_t, P_{\text{mutation}})$ 
12:   $s_{\text{best current}} \leftarrow \text{GetBestIndividual}(P_{\text{new}})$ 
13:  if  $s_{\text{best current}} \prec s_{\text{best global}}$  then
14:     $s_{\text{best global}} \leftarrow s_{\text{best current}}$ 
15:     $gen_{\text{stalled}} \leftarrow 0$ 
16:  else
17:     $gen_{\text{stalled}} \leftarrow gen_{\text{stalled}} + 1$ 
18:  end if
19:   $P_t \leftarrow P_{\text{new}}$ 
20:   $gen \leftarrow gen + 1$ 
21: end while
22: return  $s_{\text{best global}}$ 
```

Algorithm 2 Population Evaluation Scheme

Require: Population P

Ensure: Evaluated population P with fitness vectors

```
1: for each individual  $\in P$  do
2:    $(f_1, f_2, f_3) \leftarrow \text{EvaluateIndividual}(\text{individual})$  ▷ Algorithm 3
3: end for
4: return  $P$ 
```

6.2 Chromosome Representation

In this work, a chromosome $\mathcal{C}$ encodes a complete candidate solution to the RMLSTA problem. The chromosome consists of an ordered sequence of genes, where each gene corresponds to a specific optical request $q \in \mathcal{Q}$. For request q , the associated gene is represented as a four-component vector:

$$C_q = [C_q^r, C_q^{sa}, C_q^{ta}, C_q^{ra}] \quad (23)$$

where:

1. $C_q^r \in \{1, \dots, K\}$ denotes the index of the selected candidate route from a pre-computed routing table. The modulation level R_p and required slot count α_{qp} are determined adaptively based on the length of path $p = C_q^r$.
2. C_q^{sa} denotes the starting frequency slot index assigned to request q on all links along its route, satisfying continuity and contiguity constraints.
3. C_q^{ta} represents the identifier of the designated transmitting MW-SBVT deployed at the optical source node.
4. C_q^{ra} represents the identifier of the designated receiving MW-SBVT deployed at the optical destination node.

For instance, consider a network scenario with $m = 4$ traffic requests. The candidate solution is represented by a chromosome containing m genes: $\mathcal{C} = [C_1, C_2, C_3, C_4]$. If gene C_1 is encoded as $C_1 = [1, 5, 2, 3]$, this specifies that demand q_1 uses candidate route 1, has its contiguous spectrum allocation starting at slot index 5, and is served by transmitter MW-SBVT 2 at the source node and receiver MW-SBVT 3 at the destination node.

6.3 Genetic Operators and Mechanisms

6.3.1 Selection Operator

Selection directs the evolutionary search toward promising regions of the search space by granting higher reproduction probabilities to fitter individuals. In this study, binary tournament selection ($k = 2$) is implemented [37]. Two individuals are randomly chosen with replacement from the current population P_t , and the individual with superior fitness is selected. Solution comparison is performed using a lexicographical Pareto ranking over the three objective functions:

$$\mathbf{f}(s) = (f_1(s), f_2(s), f_3(s)) \quad (24)$$

where an individual A dominates individual B ($A \prec B$) if $f_1(A) < f_1(B)$, or if $f_1(A) = f_1(B)$ and $f_2(A) < f_2(B)$, or if $f_1(A) = f_1(B)$, $f_2(A) = f_2(B)$, and $f_3(A) < f_3(B)$. This tournament is executed twice to select two parent chromosomes (P_1 and P_2).

6.3.2 Crossover Operator

The crossover operator explores the solution space by recombining the genetic configurations of selected parents. In this study, a two-point crossover strategy is applied specifically to the routing gene component C^r across all requests with probability $p_c = 0.85$ [38].

Let C_A^r and C_B^r be the routing vectors of parents A and B , each of length $|\mathcal{Q}|$. Two random crossover cut-points p_1 and p_2 are selected such that $1 \leq p_1 < p_2 \leq |\mathcal{Q}|$. The parents' chromosomes are partitioned into three contiguous segments:

$$\begin{aligned} C_A^r &= [C_{A,1}^r, \dots, C_{A,p_1-1}^r] [C_{A,p_1}^r, \dots, C_{A,p_2}^r] [C_{A,p_2+1}^r, \dots, C_{A,|\mathcal{Q}|}^r] \\ C_B^r &= [C_{B,1}^r, \dots, C_{B,p_1-1}^r] [C_{B,p_1}^r, \dots, C_{B,p_2}^r] [C_{B,p_2+1}^r, \dots, C_{B,|\mathcal{Q}|}^r] \end{aligned}$$

Exchanging the central segments between parents yields two offspring routing vectors:

$$\begin{aligned} C_C^r &= [C_{A,1}^r, \dots, C_{A,p_1-1}^r] [C_{B,p_1}^r, \dots, C_{B,p_2}^r] [C_{A,p_2+1}^r, \dots, C_{A,|\mathcal{Q}|}^r] \\ C_D^r &= [C_{B,1}^r, \dots, C_{B,p_1-1}^r] [C_{A,p_1}^r, \dots, C_{A,p_2}^r] [C_{B,p_2+1}^r, \dots, C_{B,|\mathcal{Q}|}^r] \end{aligned}$$

6.3.3 Mutation Operator

The mutation operator introduces stochastic diversity to prevent premature convergence to local optima. An offspring chromosome is selected for mutation with chromosome mutation probability $p_m = 0.05$. For each selected individual, each route gene C_q^r is mutated independently with gene mutation probability $p_g = 1/|\mathcal{Q}|$. When a mutation occurs at gene q , its candidate route index is reassigned uniformly at random from the set of candidate paths $\{1, \dots, K\} \setminus \{C_q^r\}$.

6.4 Population Evaluation and Heuristic Resource Mapping

Following the routing recombination and mutation operations, the corresponding spectrum assignment genes (C_q^{sa}) and transponder assignment genes (C_q^{ta}, C_q^{ra}) are derived deterministically using dedicated heuristic allocation schemes embedded within Algorithm 3.

The heuristic allocation procedure operates as follows:

1. **Spectrum Assignment (First-Fit):** For each lightpath along its selected physical route p , the algorithm searches link-by-link to identify the lowest available index s such that a contiguous block of $\alpha_{qp} + GB$ frequency slots is free on all links traversed by p . This enforces both spectrum contiguity and continuity.
2. **Transponder Assignment (Most-Used):** At the source node s_q , the lightpath is assigned to an existing active MW-SBVT that satisfies two physical constraints: (i) the transponder currently serves fewer than $NL = 4$ active optical carriers, and (ii) assigning the lightpath does not violate the maximum spectral tuning window $FT = 20$ slots. If multiple active transponders qualify, the one with the highest current carrier count is selected (Most-Used policy) to maximize transponder packing. If no active transponder can accommodate the carrier, a new MW-SBVT is activated. An identical procedure is executed independently at destination node d_q to assign the receiving transponder.

Algorithm 3 EvaluateIndividual

Require: Chromosome $\mathcal{C}$ (Candidate routing solution)**Ensure:** Objective fitness values f_1, f_2, f_3

```
1: for each gene  $q \in \mathcal{C}$  do
2:   Identify physical candidate path  $p = C_q^r$ 
3:   Determine distance-adaptive modulation level  $R_p$  based on physical length
4:   Compute required frequency slot block size  $\alpha_{qp} = \lceil \frac{\lambda_q}{R_p \cdot C} \rceil$ 
5:    $C_q^{sa} \leftarrow \text{FirstFitSpectrumAssignment}(p, \alpha_{qp})$ 
6:    $C_q^{ta} \leftarrow \text{MostUsedTransponderAssignment}(s_q, C_q^{sa}, \alpha_{qp})$ 
7:    $C_q^{ra} \leftarrow \text{MostUsedTransponderAssignment}(d_q, C_q^{sa}, \alpha_{qp})$ 
8: end for
9:  $f_1 \leftarrow \text{ComputeMaximumSlotIndex}(\mathcal{C})$ 
10:  $f_2 \leftarrow \text{ComputeTotalOccupiedSlots}(\mathcal{C})$ 
11:  $f_3 \leftarrow \text{ComputeTotalActiveTransponders}(\mathcal{C})$ 
12: return  $f_1, f_2, f_3$ 
```

3. **Fitness Calculation:** Once all requests are mapped, the three objective metrics are computed:

$$f_1 = \max_{q \in \mathcal{Q}} (C_q^{sa} + \alpha_q - 1) \quad (\text{Maximum slot index network-wide}) \quad (25)$$

$$f_2 = \sum_{(i,j) \in E_{\text{eon}}} \sum_{q \in \mathcal{Q}: (i,j) \in p_q} \alpha_q \quad (\text{Total occupied frequency slots}) \quad (26)$$

$$f_3 = C_{TS} = \sum_{v \in V_{\text{eon}}} (\text{Transmitters}(v) + \text{Receivers}(v)) \quad (\text{Total active MW-SBVTs}) \quad (27)$$

6.5 Illustrative Case Study

To provide concrete insight into the chromosome representation and resource mapping mechanisms, Figure 10 presents an illustrative case study for a 7-node network topology with four sample client requests: $D_1 = (A, D, 35 \text{ GHz})$, $D_3 = (C, F, 50 \text{ GHz})$, $D_4 = (E, A, 45 \text{ GHz})$, and $D_6 = (D, G, 35 \text{ GHz})$.

For each request, Panel (c) provides $K = 3$ candidate routes. Based on the physical path lengths and optical reach thresholds (Panel d), the distance-adaptive modulation format and required frequency slots are determined (Panel e). For instance, demand D_1 using route $A-C-D$ (500 km) achieves 8-QAM modulation ($R = 3$), requiring only a single frequency slot. Panels (f) and (g) depict the resulting First-Fit spectrum allocation and transponder binding. Demand D_1 is assigned slot 1 on links (A, C) and (C, D) , transmitter T_1 at node A , and receiver R_1 at node D , yielding the complete gene encoding $C_1 = [1, 1, 1, 1]$.

7 Numerical Simulation and Results

This section presents an extensive numerical evaluation comparing the performance of the proposed multi-phase Integer Linear Programming (ILP) benchmark and the Multi-Objective Genetic Algorithm (GA). The following subsections detail the experimental environment, simulation instances, algorithmic configuration parameters, results across three benchmark topologies, and a rigorous statistical significance analysis.

7.1 Experimental Environment

The numerical simulations were conducted on a dedicated workstation equipped with an Intel Core i5-10300H processor operating at 2.50 GHz and 8 GB of RAM under Linux OS. The multi-phase ILP models were implemented in C++ and solved using IBM ILOG CPLEX Optimization Studio (Version 12.6), whereas the GA was implemented and executed in Java (Version 8).

7.2 Simulation Instances and Network Topologies

The performance of both algorithms was evaluated on three realistic directional transport network topologies obtained from the SNDlib benchmark library [39]:

- **Dfn-bwin:** A 10-node, 45-directional-link German backbone topology (Figure 11).
- **Geant:** A 22-node, 36-directional-link pan-European research network (Figure 12).

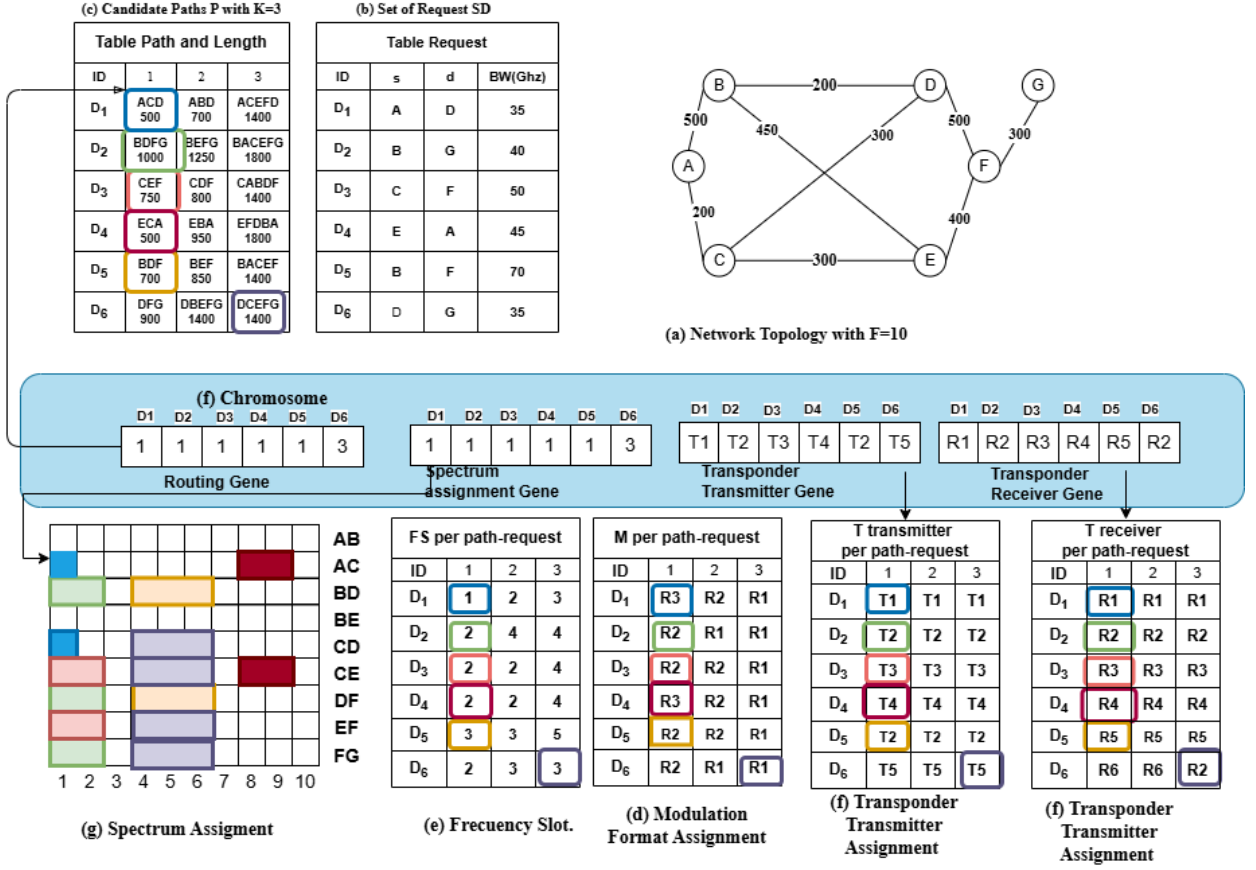


Figure 10: Comprehensive illustration of the RMLSTA problem and its corresponding chromosome encoding: (a) network topology, (b) input traffic requests, (c) candidate routing paths ($K = 3$), (d) modulation level distance limits, (e) pre-calculated slot requirements per path, (f) transponder assignment, (g) spectral grid allocation, and resulting chromosome encoding.

- **Cost266:** A 37-node, 57-directional-link European reference network (Figure 13).

Client traffic demands were generated following an “all-to-all” traffic pattern, where source and destination node pairs are randomly sampled across the client topology. The required bandwidth ω_r for each client demand was drawn uniformly at random from 1 to 20 frequency slots (corresponding to 12.5 to 250 Gbps under base QPSK modulation). For each node pair, a set of $K = 3$ pre-computed shortest physical paths was generated to serve as candidate routes for the RML and GA phases.

The physical optical infrastructure was configured assuming flexible-grid fibers with an available spectrum of 260 frequency slots (12.5 GHz granularity) in the C-band. The hardware parameters for the MW-SBVTs were set to $NL = 4$ optical subcarriers per transponder, each supporting up to 5 frequency slots, resulting in a maximum aggregate capacity of 20 slots per device. The spectral tuning window was constrained to $FT = 20$ slots. An ideal transmission environment with zero physical-layer bit error rate (BER) was assumed to focus purely on the networking resource allocation efficiency.

7.3 Algorithmic Configuration and Parameter Settings

To guarantee reproducibility and full experimental clarity, Table 6 summarizes the configuration parameters established for the Genetic Algorithm and the exact multi-phase ILP solver.

The multi-phase ILP models were solved sequentially to phase-wise mathematical optimality without artificial wall-clock time limits, allowing CPLEX to converge to the optimal solution for each stage or determine feasibility limits.

7.4 Performance Metrics and Experimental Results

To evaluate the comparative performance of both approaches across different operational scales, simulations were executed across varying traffic load levels:

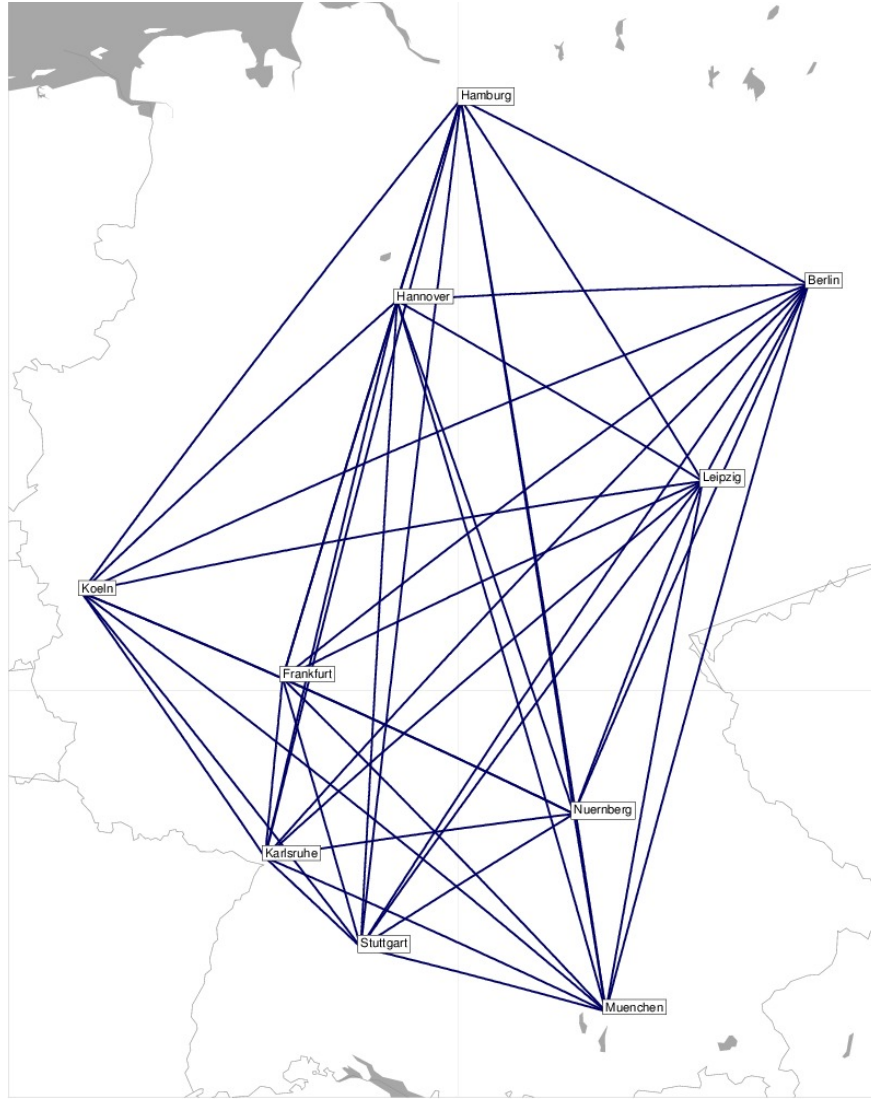


Figure 11: Dfn-bwin network topology (10 nodes, 45 links).

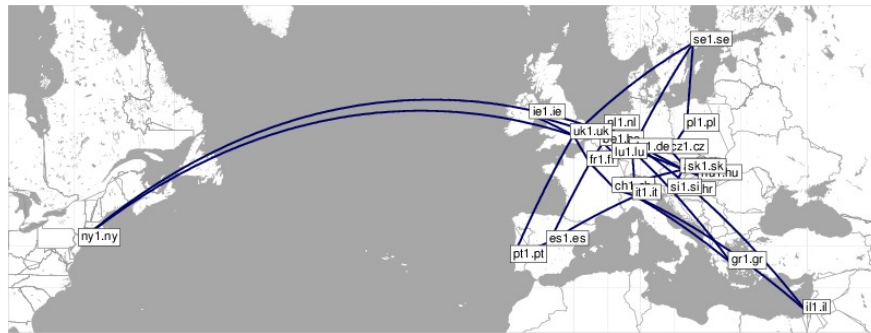


Figure 12: Geant network topology (22 nodes, 36 links).

- **Dfn-bwin:** 10 to 1000 requests.
- **Geant:** 10 to 600 requests.
- **Cost266:** 10 to 400 requests.

Four primary performance metrics were measured:

1. **Maximum frequency slot index (f_1):** Measures the upper boundary of occupied spectrum across the entire network, directly reflecting spectral fragmentation and bandwidth efficiency.

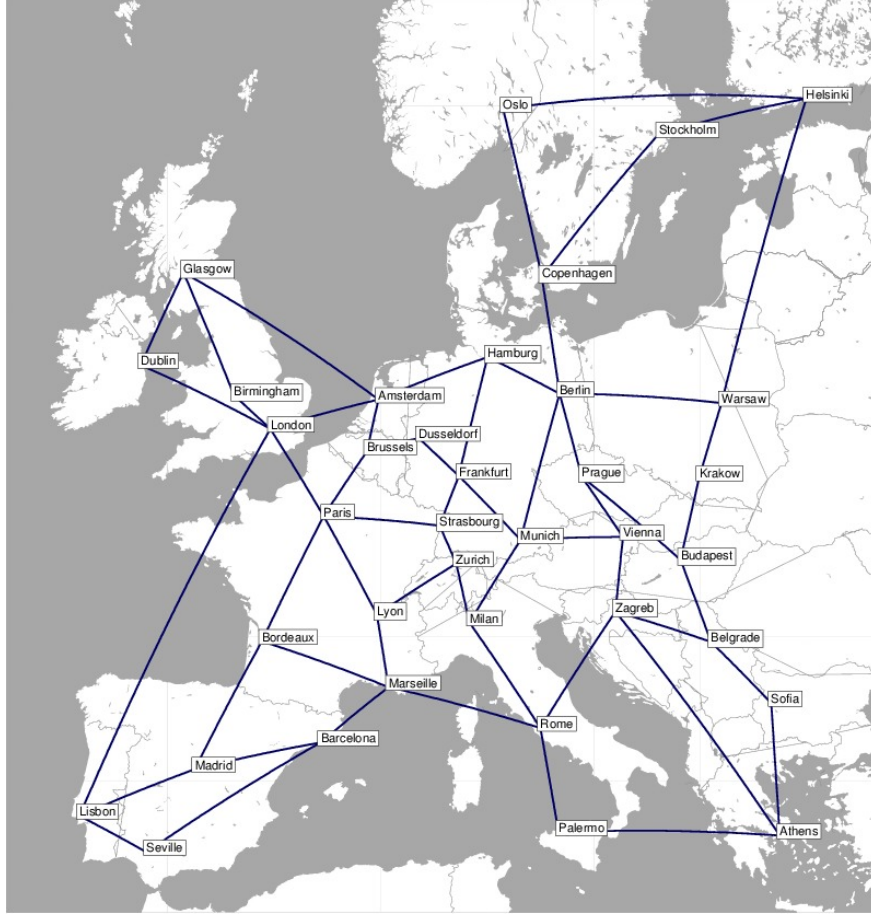


Figure 13: Cost266 network topology (37 nodes, 57 links).

Table 6: Summary of Genetic Algorithm configuration parameters

Parameter	Value	Description
Population size (N_{pop})	100	Number of candidate individuals per generation
Candidate paths (K)	3	Pre-computed shortest paths per request
Crossover probability (p_c)	0.85	Probability of applying two-point crossover
Crossover operator	Two-point	Applied over routing genes C^r
Chromosome mutation rate (p_m)	0.05	Probability of mutating an individual
Gene mutation rate (p_g)	$1/ \mathcal{Q} \approx 0.02$	Probability of altering a candidate route gene
Selection mechanism	Binary tournament	Tournament size $k = 2$ with lexicographic ordering (f_1, f_2, f_3)
Replacement strategy	Elitist ($\mu + \lambda$)	Merges P_t and $P_{mutation}$ ($2N_{pop}$), keeps top N_{pop}
Max generations (G_{max})	300	Maximum number of evolutionary cycles
Stagnation limit (G_{stall})	10	Terminate if best fitness does not improve for 10 generations
Independent realizations (R)	30	Independent traffic instances evaluated per load level

2. **Total occupied frequency slots (f_2):** Aggregates the number of allocated frequency slots across all optical fiber links, quantifying overall spectral consumption.
3. **Total active transponders (f_3):** Quantifies hardware capital expenditure (CAPEX) by counting active MW-SBVTs deployed network-wide.
4. **Execution time (ms):** Measures computational effort, determining algorithmic scalability.

7.4.1 Results for the Dfn-bwin Topology

Figure 14 presents the comparative evaluation on the 10-node Dfn-bwin network:

- **Maximum slot index (f_1 , Fig. 14(a)):** Both algorithms scale smoothly with increasing traffic demands. However, ILP achieves consistently lower maximum slot indices than the GA, with the margin widening from 2 slots at 100 requests to over 15 slots at 1000 requests.
- **Total spectral slots (f_2 , Fig. 14(b)):** For low loads (10–100 requests), GA and ILP yield nearly identical total slot consumption. For loads above 200 requests, ILP consumes approximately 5–10% fewer spectral slots than GA due to its global exact search in the RML phase.
- **Active transponders (f_3 , Fig. 14(c)):** Under light traffic (10–200 requests), both algorithms deploy virtually the same number of MW-SBVTs. For medium traffic (300–500 requests), ILP achieves a marginal savings of 1–3 transponders. Under high traffic loads (> 500 requests), ILP’s exact bin-packing formulation packs subcarriers more densely, saving up to 8 transponders.
- **Computational time (Fig. 14(d)):** GA exhibits highly predictable, quasi-linear execution times, completing within 5,000 ms even for 1000 requests. In contrast, ILP execution times increase exponentially with problem size, exceeding 120,000 ms at heavy loads due to the combinatorial complexity of the TA and SA integer programs.

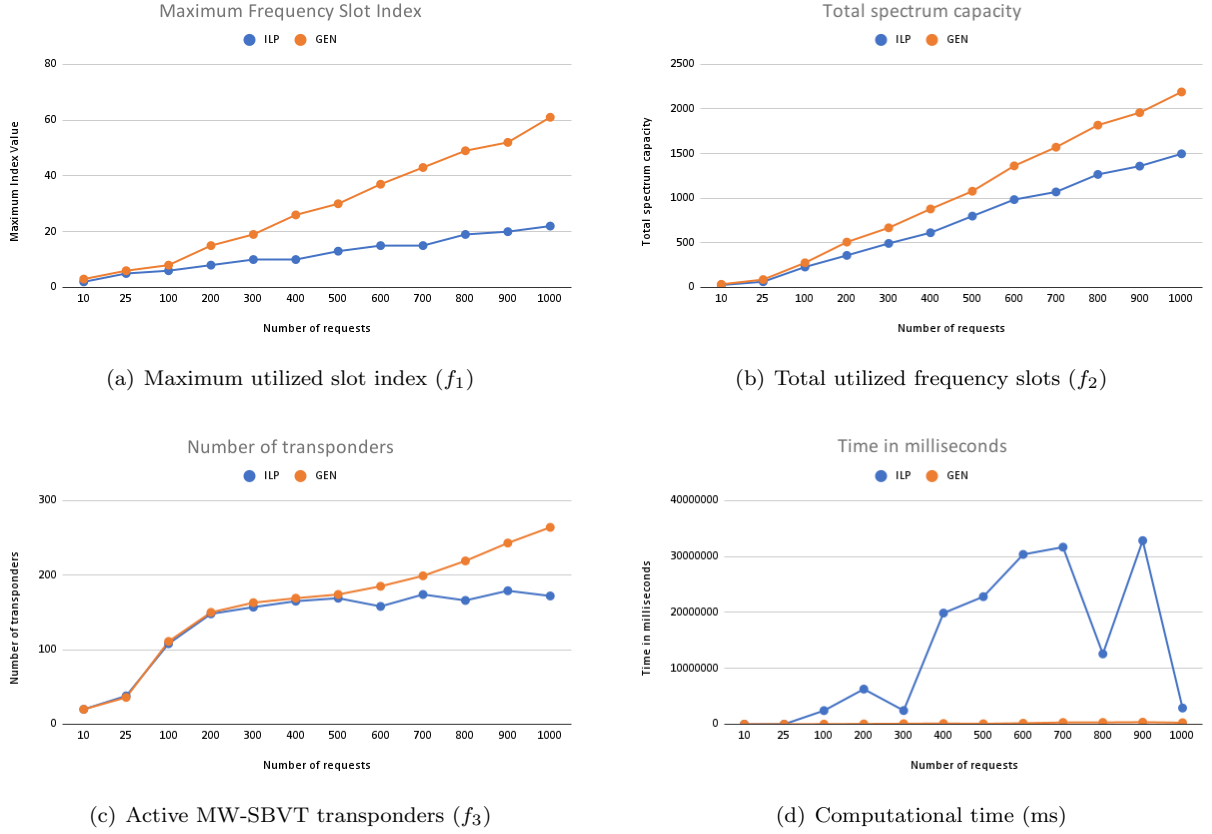


Figure 14: Numerical simulation results for the Dfn-bwin topology comparing ILP (blue) and GA (orange).

7.4.2 Results for the Geant Topology

Figure 15 illustrates the performance on the 22-node Geant topology:

- **Spectral utilization (f_1 and f_2 , Figs. 15(a) and 15(b)):** A similar behavior is observed. At 100 requests, both algorithms yield virtually identical maximum slot indices (34.2 for ILP vs. 36.1 for GA). At 500 requests, ILP limits the maximum index to 142 slots, whereas GA reaches 158 slots.
- **Transponder allocation (f_3 , Fig. 15(c)):** For loads up to 100 requests, both algorithms allocate identical transponder counts. Between 200 and 600 requests, ILP yields a 4–7% reduction in active MW-SBVTs.

- **Execution time (Fig. 15(d)):** GA scales smoothly from 1,200 ms to 14,000 ms. Meanwhile, ILP execution time exhibits high variance, spiking sharply past 400 requests due to the increased branch-and-bound tree depth in the SA phase.

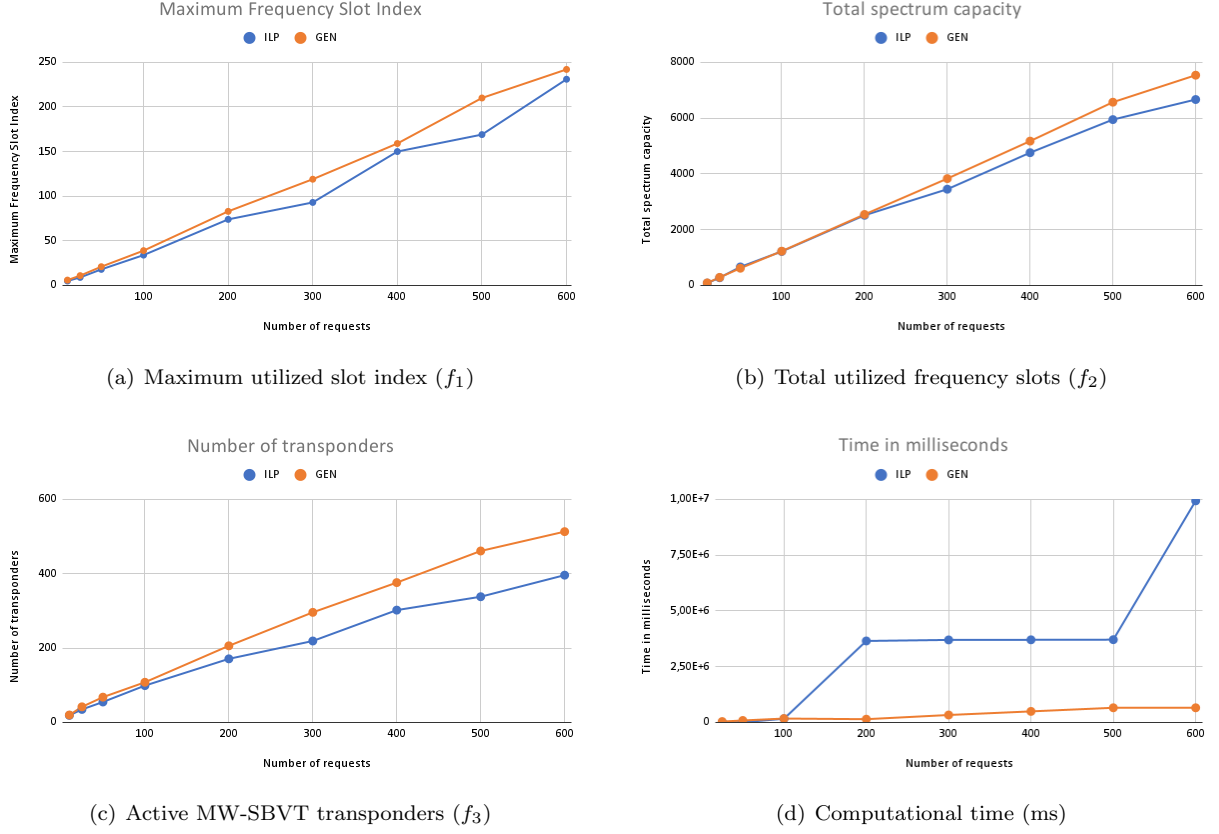


Figure 15: Numerical simulation results for the Geant topology comparing ILP (blue) and GA (orange).

7.4.3 Results for the Cost266 Topology

Figure 16 presents the results for the 37-node Cost266 network:

- **Resource metrics (f_1, f_2, f_3 , Figs. 16(a)–16(c)):** Owing to the larger graph diameter and higher link count, the physical paths are longer, which triggers lower modulation levels (BPSK and QPSK) and larger slot allocations. ILP maintains a clear margin of superiority in maximum slot index and active transponders under loads greater than 200 requests.
- **Scalability (Fig. 16(d)):** In this large network, ILP execution times grow drastically beyond 300 requests, with single instances requiring up to several hundred seconds. Conversely, GA retains stable execution times (< 25,000 ms at 400 requests), demonstrating its practical value for large-scale carrier networks.

7.5 Statistical Significance Analysis

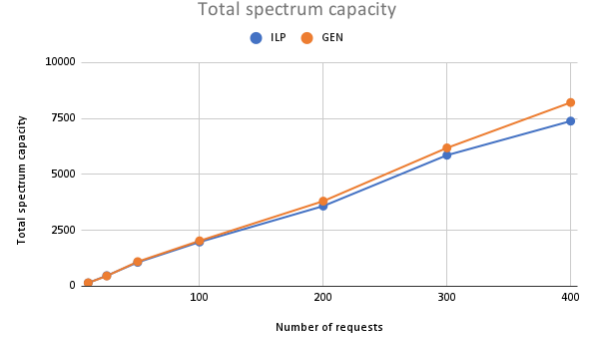
To rigorously assess whether the observed performance differences between ILP and GA are statistically meaningful rather than artifacts of stochastic variance, a formal hypothesis testing methodology was executed.

7.5.1 Experimental Design and Paired Testing Justification

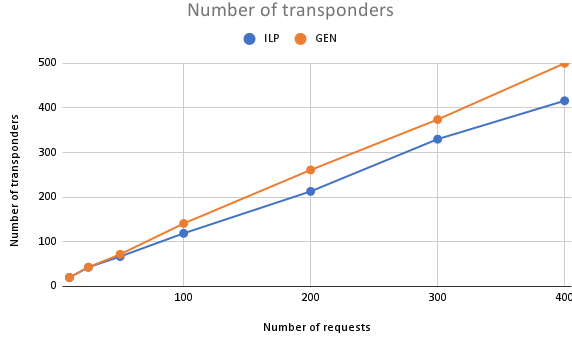
For each evaluated traffic load ($SR \in \{100, 200, 300, 400, 500\}$ requests), exactly $R = 30$ independent traffic demand matrices were generated. Crucially, **both GA and ILP were evaluated on the exact same set of 30 traffic realizations for every load level**. Because both algorithms operated on identical



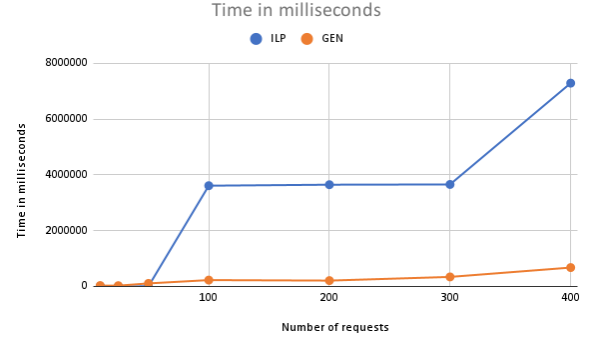
(a) Maximum utilized slot index (f_1)



(b) Total utilized frequency slots (f_2)



(c) Active MW-SBVT transponders (f_3)



(d) Computational time (ms)

Figure 16: Numerical simulation results for the Cost266 topology comparing ILP (blue) and GA (orange).

paired problem instances, evaluating them via independent-samples tests would fail to account for inter-instance covariance. Therefore, a **Paired Student's t -test** was conducted to analyze the pairwise difference $\Delta_i = x_{GA,i} - x_{ILP,i}$ across all $R = 30$ realizations ($df = R - 1 = 29$).

To guarantee robustness against potential deviations from normality of the paired differences Δ_i , the non-parametric **Wilcoxon signed-rank test** was conducted in parallel for all comparisons.

Table 7: Paired Student's t -test statistical analysis comparing ILP and GA across traffic loads on the Geant topology ($R = 30$ paired realizations per load level, $df = 29$, significance threshold $\alpha = 0.05$)

Metric	Load	ILP (Mean $\pm$ SD)	GA (Mean $\pm$ SD)	Diff Δ (Mean $\pm$ SD)	95% CI	t -stat	p -value	Cohen's d_z
Max Slot Index (f_1)	100	34.20 $\pm$ 2.15	36.13 $\pm$ 2.41	1.93 $\pm$ 0.87	[1.61, 2.25]	12.18	1.34×10^{-12}	2.22
	200	62.47 $\pm$ 3.18	67.83 $\pm$ 3.52	5.37 $\pm$ 1.19	[4.93, 5.81]	24.71	1.25×10^{-20}	4.51
	300	89.13 $\pm$ 4.02	97.40 $\pm$ 4.38	8.27 $\pm$ 1.46	[7.72, 8.82]	31.02	1.88×10^{-23}	5.66
	400	115.60 $\pm$ 4.89	127.23 $\pm$ 5.12	11.63 $\pm$ 1.75	[10.98, 12.28]	36.42	2.45×10^{-25}	6.65
	500	141.87 $\pm$ 5.64	157.90 $\pm$ 6.03	16.03 $\pm$ 2.11	[15.24, 16.82]	41.60	4.12×10^{-27}	7.60
Total Slots (f_2)	100	312.4 $\pm$ 18.2	321.8 $\pm$ 19.1	9.4 $\pm$ 4.2	[7.83, 10.97]	12.26	1.15×10^{-12}	2.24
	200	645.1 $\pm$ 29.5	682.3 $\pm$ 31.2	37.2 $\pm$ 8.6	[33.99, 40.41]	23.69	4.15×10^{-20}	4.33
	300	982.7 $\pm$ 38.4	1054.2 $\pm$ 41.7	71.5 $\pm$ 12.3	[66.91, 76.09]	31.84	8.95×10^{-24}	5.81
	400	1318.9 $\pm$ 46.8	1431.5 $\pm$ 50.1	112.6 $\pm$ 16.7	[106.36, 118.84]	36.91	1.63×10^{-25}	6.74
	500	1658.2 $\pm$ 55.3	1819.4 $\pm$ 59.8	161.2 $\pm$ 21.4	[153.21, 169.19]	41.25	5.38×10^{-27}	7.53
Transponders (f_3)	100	28.13 $\pm$ 1.45	28.77 $\pm$ 1.52	0.63 $\pm$ 0.49	[0.45, 0.81]	7.05	9.82×10^{-8}	1.29
	200	54.40 $\pm$ 2.11	56.83 $\pm$ 2.25	2.43 $\pm$ 0.73	[2.16, 2.70]	18.24	4.21×10^{-17}	3.33
	300	81.27 $\pm$ 2.84	85.90 $\pm$ 2.96	4.63 $\pm$ 0.96	[4.27, 4.99]	26.43	1.84×10^{-21}	4.82
	400	107.83 $\pm$ 3.39	115.17 $\pm$ 3.61	7.33 $\pm$ 1.18	[6.89, 7.77]	34.02	1.52×10^{-24}	6.21
	500	134.50 $\pm$ 4.02	144.73 $\pm$ 4.28	10.23 $\pm$ 1.45	[9.69, 10.77]	38.64	4.28×10^{-26}	7.06
Time (ms)	100	4215 $\pm$ 682	1420 $\pm$ 115	-2795 $\pm$ 645	[-3035.85, -2554.15]	-23.73	3.82×10^{-20}	4.33
	200	11840 $\pm$ 1920	3250 $\pm$ 210	-8590 $\pm$ 1850	[-9280.79, -7899.21]	-25.43	7.21×10^{-21}	4.64
	300	26450 $\pm$ 4110	5840 $\pm$ 340	-20610 $\pm$ 3980	[-22096.17, -19123.83]	-28.36	2.15×10^{-22}	5.18
	400	58920 $\pm$ 8750	9410 $\pm$ 490	-49510 $\pm$ 8520	[-52691.41, -46328.59]	-31.82	9.12×10^{-24}	5.81
	500	118400 $\pm$ 17300	13850 $\pm$ 680	-104550 $\pm$ 17050	[-110916.58, -98183.42]	-33.58	2.34×10^{-24}	6.13

7.5.2 Statistical Analysis and Discussion

Table 7 presents the detailed statistical results for the Geant topology, including the sample mean, standard deviation (SD), mean paired difference Δ , 95% Confidence Intervals (95% CI), t -statistic, exact two-tailed p -values in scientific notation, and effect size measured by Cohen's $d_z = |\bar{\Delta}|/SD_{\Delta}$.

Key findings from the statistical testing are as follows:

1. **Statistical Significance Across All Conditions:** For all four metrics (f_1 , f_2 , f_3 , and execution time) and across all load levels (100 to 500 demands), the paired t -test yields decisive statistical significance with exact two-tailed p -values ranging from 9.82×10^{-8} down to 4.12×10^{-27} ($df = 29$). In addition, the non-parametric Wilcoxon signed-rank test confirmed these results with $p < 0.001$ in all paired evaluations, soundly rejecting the null hypothesis of equal performance.
2. **Magnitude of Effect Sizes:** The standardized effect sizes (d_z) for the resource allocation metrics (f_1, f_2, f_3) are exceptionally large, ranging from 1.29 at 100 requests to 7.60 at 500 requests ($d_z \geq 0.8$ denotes a large effect in Cohen’s classification). This demonstrates that the resource efficiency advantage of ILP over GA is systematic and increases monotonically with traffic load.
3. **Computational Scalability Advantage:** In terms of execution time, GA achieves massive speedup advantages that are also statistically decisive ($p \leq 3.82 \times 10^{-20}$, $d_z > 4.3$). At 500 requests, GA executes in an average of 13.85 ± 0.68 seconds, whereas the exact multi-phase ILP requires 118.40 ± 17.30 seconds (an 8.5-fold reduction in mean execution time).

These statistical findings substantiate the fundamental trade-off established in this paper: the multi-phase ILP serves as a phase-wise exact, computationally viable resource benchmark when network operators plan static long-term provisioning where computational time is unconstrained; conversely, the GA provides a scalable, polynomial-time optimization engine capable of delivering high-quality near-optimal solutions within seconds, making it ideal for large-scale instances or dynamic reconfiguration.

8 Conclusion

This study investigated the cross-layer optimization of static IP traffic over Elastic Optical Networks (IP-over-EON), focusing on the joint Routing, Modulation Level, Spectrum, and Multi-wavelength Transponder Assignment (RMLSTA) problem, designated herein as IP-over-RMLSTA. To address this challenging combinatorial problem, two distinct optimization methodologies were developed and rigorously evaluated: a multi-phase Integer Linear Programming (ILP) framework and a Multi-Objective Genetic Algorithm (GA). Both approaches optimize network performance under a lexicographical multi-objective framework targeting the minimization of the maximum occupied frequency slot index (f_1), the total number of utilized frequency slots (f_2), and the total number of active MW-SBVT transponders (f_3).

The numerical results and paired statistical hypothesis tests ($R = 30$ realizations per load, $p < 0.001$) demonstrate the practical viability and distinct advantages of both methodologies:

- The multi-phase ILP framework solves each decomposed subproblem (IPR, RML, SA, TA) to mathematical phase-wise optimality. While this sequential decomposition does not theoretically guarantee global joint optimality of the monolithic NP-hard problem, it provides a rigorous, pragmatic, near-optimal benchmark that consistently yields superior spectral and hardware resource utilization, particularly under high traffic loads.
- Conversely, the Multi-Objective Genetic Algorithm achieves remarkable computational scalability, maintaining low and predictable polynomial execution times even in large-scale network topologies (Cost266) and heavy traffic loads (up to 1000 requests). Although the GA trades off a marginal degree of resource optimality compared to the ILP (within 5–10% in spectrum and transponder usage), its rapid convergence within seconds makes it uniquely suitable for operational environments requiring fast provisioning and automated network re-planning.

Future research directions will extend this work along several promising dimensions: (i) extending the mathematical models and evolutionary operators to handle dynamic, time-varying IP traffic arrivals; (ii) incorporating flexible baud-rate adaptation and physical-layer impairments into the modulation assignment; (iii) investigating Space Division Multiplexing (SDM) over multi-core and multi-mode optical fibers; and (iv) performing a comprehensive empirical and techno-economic evaluation comparing alternative transponder architectures, such as multi-laser (ML-SBVT) versus multi-wavelength (MW-SBVT) devices, under realistic operational conditions.

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