Novel Genetic Algorithm for Routing and Wavelength Assignment in Elastic Optical Networks

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Abstract. This paper introduces a novel algorithm for Routing and Wavelength Assignment (RWA) in Elastic Optical Networks (EONs), designed to enhance overall network efficiency and performance. The proposed algorithm will handle both single-hop and multi-hop grooming strategies; thus, the offered total resource utilization and spectrum efficiency under dynamic traffic demands are ensured to be optimum. MBP, which is the Mean Blocking Probability, quantifies, measures bandwidth usage efficiency; and finally, Jain's Fairness Index (JFI), which assesses fairness in the distribution of resources among users. The proposed algorithm, in minimising the blocking probability, enhancing bandwidth utilisation, and ensuring fair resource allocation, is proved to reduce critical challenges with EONs and, thus, offers a cost-effective, adaptive, efficient, and fair solution for the growing demand for high-bandwidth services.

Keywords: EON , RWA , Genetic Algorithm , JFI , WDM , NSFNet , Eurocore .

1 Introduction

The requirement for high-bandwidth services has accelerated the development of Elastic Optical Networks (EONs), which offer greater adaptability, efficient spectrum utilization, and optimized performance across classes of service compared to traditional WDM systems. EONs dynamically allocate spectrum resources to match traffic demands, thereby providing better bandwidth granularity and reducing the need for overprovisioned resources.

A critical challenge in EONs is the Routing and Wavelength Assignment (RWA) problem, where routing paths and wavelengths must be assigned to traffic flows in an efficient manner. This problem has a significant impact on network performance metrics such as blocking probability, bandwidth utilization, and fairness. Numerous algorithms have been developed to tackle the RWA problem, each designed to improve different performance aspects of the network.

This research investigates various RWA algorithms within single-hop and multi-hop grooming environments, using key metrics like Mean Blocking Probability (MBP), Mean Bandwidth Blocking Ratio (MBBR), and Jain's Fairness Index (JFI) to assess algorithm efficiency under fluctuating traffic conditions. Building on foundational studies, the project draws insights from a range of strategies: the integration of SDN controllers with Quantum Key Distribution for enhanced security and resource management [1] a proactive, self-regulated ant-based RWA protocol for load balancing in WDM networks [2] an automated distributed dynamic survivable RWA protocol to bolster resource allocation robustness [3] and an efficient alternate RWA protocol to improve lightpath selection under network congestion [4] Further contributions include a centralized RWA protocol designed to minimize request rejection [5] and a priority-based traffic balancing protocol that helps optimize performance for various traffic classes [6]

Genetic Algorithm (GA) is used in our novel algorithm because of its ability to efficiently solve complex optimization problems that involve multiple conflicting objectives and constraints. GAs are quite different from conventional algorithms, as they incorporate intrinsic adaptability and an ability to explore a large solution space to identify globally optimal solutions. This allows GAs to be particularly well-suited for the RWA problem in EONs, where the dynamic and heterogeneous nature of traffic demands requires a flexible and robust approach. Leverage on the evolutionary nature of GAs to propose an algorithm that improves upon resource allocation, minimizes blocking probability, and consequently provides better overall network performance against diverse traffic scenarios.

By synthesizing these diverse approaches, this research offers an extensive evaluation of RWA algorithms, advancing our understanding of optimizing resource allocation and network performance in EONs under variable traffic demands.

2 Literature Survey

S.Shrivastava et al. [1] proposes a solution for enhancing security in optical networks through Quantum Key Distribution (QKD) integrated with Wavelength Division Multiplexing (WDM), pointing towards the vulnerabilities of classical cryptographic systems that arise from quantum computing. From the perspective of quantum computing attacks, previous studies have shown the weaknesses of optical fibers against eavesdropping and show the limitations of classical encryption, especially in high-security domains. While QKD offers strong protection, synchronization conflicts arise with static Routing and Wavelength-Time Assignment (RWTA) strategies when multiple requests overlap in wavelength and time. This work introduces a Time Sliding Window-enabled RWTA, managed by an SDN controller, to resolve these conflicts and ensure secure, flexible communication.

T.K. Ramesh et al. [2] proposes an Ant Colony Optimization (ACO) solution for the Routing and Wavelength Assignment (RWA) problem in Wavelength Division Multiplexing (WDM) networks. . Classic RWA methods face scalability problems due to wavelength continuity constraints and complexity of computation. This new approach uses "ants" as control agents to gather dynamic network status for realizing adaptive path selection based on real-time load, thereby self-adjusting for variations in traffic, enhancing bandwidth usage, and survivability in the network. Simulation results demonstrate the ACO-based protocol has the capability to increase throughput and bandwidth efficiency in WDM networks.

T.K. Ramesh et al. [3] addresses the challenge of efficient traffic grooming and Routing and Wavelength Assignment (RWA) in Wavelength Division Multiplexing (WDM) networks, which serve as a high-capacity backbone for data transmission. Methods for RWA are essential to establishing lightpaths in optical networks but encounter scalability issues and suffer WCC and network failures critical for both service quality and survivability. Traditional centralized RWA control has the scalability issue, while distributed control cannot achieve complete network information. In order to enhance lightpath setup time and to minimize network blocking, this paper proposed a protocol which will automatically update the network information at each node in such a way that lightpath selection will be optimized according to the available wavelengths and distance. The simulation results are given that this combined approach offers better blocking performance. WCC will be overcome using wavelength converters and reassignment techniques in the future work.

R. Janani et al. [4] presents an Efficient Alternate Routing Protocol (EARP) to address the Routing and Wavelength Assignment (RWA) problem in Wavelength Division Multiplexing (WDM) networks. Critical to this is the development of data-intensive applications of all-optical infrastructure, this consideration somehow specifically requiring an alternate strategy for the WDM networks, which will help with the inevitable challenges of optimal lightpath selection and network survivability. In ERAP, lightpath selection is optimized by balancing distance with network congestion. Destination initiated reservation (DIR) has further reduced delay and race conditions. Simulation results indicate low blocking probabilities, and further work will be aimed toward introducing traffic grooming for the efficient use of resources.

S.K. Konda et al. [5] details an Advanced Centralized Routing and Wavelength Assignment Protocol for Wavelength Division Multiplexing networks that aim at the improvement of network performance due to the shortcomings of the Wavelength Continuity Constraint and the high request rejection rate. ACRP makes use of a proactive method with tasks divided between two central management systems for improved Quality of Service. Unlike the reactive approaches, ACRP adjusts traffic load variation and then establishes dynamic lightpaths with optimal bandwidth usage. Simulation results prove the efficacy of the protocol in decreasing request rejections and setup times to further improve network efficiency.

P.L.S Rao et al. [6] focuses on increasing bandwidth demands in IT and focuses on WDM technologies in high-bandwidth applications. Increased demand was destined for MDONs in inter-domain connections as these were initially managed with single-domain networks. The authors discuss Scheduled Light-Path Demands and propose a heuristic algorithm on traffic balancing across time windows to address RWA constraints, more precisely the WCC. Since the algorithm enforces high-priority requests through channel grooming, it reduces blocking probability and allows more connections than any other traffic-balancing method.

W. Li et al. [7] discusses the requirements placed on optical networks by 5G networks, and to this end, identifies routing wavelength assignment challenges as optical networks are developed towards SDON technology. They further discuss existing work, such as ant colony and tabu search algorithms, for routing wavelength assignment but finds limitations for static problems. For efficiency improvement, it proposes a static routing wavelength assignment using the K-Shortest Path (K-SP) algorithm along with genetic optimization for better wavelength distribution. The simulation results on NSFNET show that the proposed method is effective for static routing wavelength assignment in optical networks.

V.S. Shekhwawat et al. [8] addressed the Routing and Wavelength Assignment (RWA) problem in Wavelength Division Multiplexing (WDM) networks. They proposed a weightbased Edge Disjoint Path algorithm with the objective of optimizing the wavelength resources in such networks. Simulation showed that the choice of light paths depends a lot on network topology, and the usage of links while selecting light paths impacts a lot on wavelength efficiency. With the proposed algorithm, the result is better wavelength utilization; it is more significant for large networks, as it has a larger size of networks and requests are of high number. As the node and request frequency increases, the required wavelengths decreases as compared to current mechanisms. Therefore, they can be used in the context of dynamic traffic for blocking probability estimation.

T.M.Rao et al. [9] suggests PSO as an algorithm to solve the NP-complete Routing and Wavelength Assignment (RWA) problem in optical networks. The algorithm is implemented using PSO, where the search for near-optimal solutions is driven by minimizing the wavelength requirement of the network and average path lengths. The Java-based network simulator implementing the PSO approach is applied to various networks, where optimal and near-optimal results are found. This novel approach clearly depicts the efficiency of PSO in RWA without wavelength conversion, hence providing a novel solution to the problems posed by complex optical networks.

K. Christodoulopoulos et al. [10] adresses the offline RWA problem in transparent all-optical networks where physical layer impairments degrading signal quality are considered without regenerators. Two IA algorithms are proposed,the first indirectly limits impairment-generating sources, and the second directly models physical impairments using noise-related constraints. Both of them aim at balancing network efficiency and transmission quality by optimizing lightpath selection to meet physical and network layer objectives. The simulation results also indicate that these IA-RWA algorithms improve wavelength utilization and blocking probability when working under realistic conditions.

O. Awwad et al. [11] addresses the Routing and Wavelength Assignment problem for DWDM networks with sparse wavelength conversion and traffic grooming. It proposes two heuristics, one based on maximizing contiguous wavelength resources, which reduces wavelength fragmentation as well as wavelength conversion and the other based on genetic adaptation using a genetic algorithm in adapting to minimize the costs for traffic grooming and wavelength conversion. These methods are demonstrated to improve the resource utilization efficiency without compromising the network blocking performance even in large networks. Future work will be focused on studying the performance of heuristics under dynamic traffic conditions.

U. Bhanja et al. [12] presents a QoS-aware Fuzzy logic-based dynamic routing and wavelength assignment (QoS-FDRWA) algorithm for WDM optical networks, designed to reduce blocking probability and execution time by incorporating network metrics like latency, link length, and wavelength availability. QoS-FDRWA Algorithm uses two fuzzy logic controllers for dynamic path optimization and reduction of path-dependent impairments such as chromatic dispersion and crosstalk. The results obtained show that large improvements in the wavelength availability and blocking probability in the performance areas, with significant conditions under a heavy network load, make this algorithm applicable for the real-time multimedia application with changing network conditions.

Q. Wu et al. [13] presents a colored multigraph model for the representation of temporarily available wavelengths in WDM networks. Based on this model, an optimized dynamic routing and wavelength assignment by a polynomial-time algorithm of time complexity $O(n\hat{2})$. (where n denotes the number of nodes) is presented. The proposed scheme reduces wavelength conversion and enhances blocking performance, which is achieved by integrating routing and wavelength assignment. Simulation results indicate that this algorithm effectively enhances network performance.

Cedeno et al. [14] discusses Elastic Optical Networks Routing, Modulation-Level, and Spectrum Assign-ment (RMLSA). It deals with spectral fragmentation problems in fixed grid Wavelength Division Multiplexing (WDM) sys-tems to support EONs with reduced frequency slot unit sizes.They also explain the potential of new methods by the non-scalar nature of optimal solutions as well as review the simplified and optimization solutions. Li et al. [15] introduced a Tradeoff-RnI algorithm for optical Network with the objective of managing spectrum usage versus boundary blocking. The comparative studies with UNB24 and NSF-Net demonstrate that small values of spectrum consumption (R) and interval size (I) are effective at controlling low traffic while larger values become helpful in lowering blocking rates as traffic grows; this, in effect, permits the algorithm to perform better than other methods overall.

Brasileiro et al. [16] presents a Fuzzy Logic-based approach for routing in Optical Networks, to reduce rate of spectral fragmentation. Blocking rate drops from 15.23%, 1.80%, and 1.36% for Dijkstra, Pseudo Partition, and Complete

Sharing algorithms, respectively. Thus, it proves its worth in reducing the level of fragmentation in optical networks.

Chai et al. [17] introduces a modified Routing and Spectrum Allocation (RSA) algorithm that includes a model for Optical Signal-to-Noise Ratio (OSNR) impairment . By checking both Quality of Transmission (QoT) and spectrum availability, the main aim of the algorithm is to reduce traffic blocking rates by modifying transmission efficiency . Theoretical analysis and simulations show that traditional RSA methods are outperformed by this approach , giving better transmission quality and lower blocking rates. By incorporating QoT assessments into the RSA process ,this method advances the design of high-capacity optical networks.

Zhang et al. [18] introduces a Routing and Spectrum Allocation (RSA) algorithm focused on Maximum Spectrum Completeness (MSC). The main aim of the algorithm is to choose contiguous frequency slots along the light path to minimize bandwidth fragmentation. It operates in three steps: The k-shortest path algorithm is used to identify optimal routes , choosing the spectrum with the least remaining slots via the Exact Fit scheme, and based on a completeness formula allocating the spectrum. The results of the simulation demonstrate that the MSC algorithm reduces probability of blocking by around 19.8 percent compared to the First-Fit (FF) scheme and around 7.1 percent compared to the Exact Fit (EF) scheme, which modifes spectrum utilization in optical networks.

Garrido et al. [19] introduces the RCMLSA algorithm, which by dynamically selecting coding schemes alongside routing and spectrum choices based on bandwidth requirements modifies performance in Optical Networks. Simulation results on the NSFNet topology show that the RCMLSA algorithm significantly outperforms both Routing and Spectrum Assignment (RCSA) and Routing, Modulation Level, and Spectrum Assignment (RMLSA) algorithms, achieving over an order of magnitude reduction in blocking rates for traffic loads below 0.7 compared to RCSA. It is shown how important of adaptive coding and modulation is in optimizing resource allocation in EONs.

Zhang et al. [20] introduces a bandwidth defragmentation algorithm designed for Optical Networks (EONs), to minimize traffic disruptions while aiming at improving spectrum utilization. The algorithm tells us when and how to defragment by selectively rerouting about 30 percent of existing connections, achieving a bandwidth blocking probability (BBP) comparable to a scenario with full rerouting. The use of the HUSIF strategy for selecting critical connections enhances BBP and reduces bandwidth fragmentation. Additionally, simulations show that traffic disruption remains below 1 percent for 30 percent rerouting and can be further reduced to 0.25 percent with a move-to-vacancy (MTV) strategy, highlighting effective bandwidth management in dynamic EONs.

Chu et al. [21] address the importance of wavelength-routed all-optical wavelength division multiplexing (WDM) networks for next-generation backbone networks. Challenges are faces by these networks in wavelength continuity constraint, which can lead to blocking when no common free wavelength is available, because it requires a consistent wavelength across all lightpath links.The authors explore wavelength conversion-particularly sparse wavelength conversion, for specific wavelength adjustments at specific routers to alleviate blocking. Their simulation results show that the WLCR-FF algorithm reduces blocking even more compared to traditional RWA strategies, showing the advantages of integrating RWA with wavelength conversion.

Banerjee et al. [22] discuss how Wavelength Division Multiplexing (WDM) facilitates the division of fiber bandwidth into multiple asynchronous channels operating at different speeds. In WDM networks, lightpaths—optical channels spanning multiple fiber links—must adhere to the wavelength continuity constraint, which requires that the same wavelength be maintained throughout their route. The Routing and Wavelength Assignment (RWA) problem,which focuses on efficiently assigning routes and wavelengths to these lightpaths, is known for its computational complexity. To tackle this problem, the authors use approximation algorithms with the aim of reducing the number of needed wavelengths. For the static scenario, where all lightpath requests are predetermined, a linear programming (LP) method with subproblem decomposition is employed. In contrast, for the dynamic scenario, where requests arrive sequentially, heuristic approaches are applied. The resulting solutions demonstrate close alignment with the lower bound on wavelength usage.

Chen et al. [23] adresses an efficient two-step approximation algorithm for multicast routing and wavelength assignment in Wavelength-Division-Multiplexing (WDM) networks ,important to support the slice of next-generation multimedia applications, like video-conferencing and HDTV. Multicast-efficient approaches pose a few problems for the authors, who manage such issues as bandwidth, wavelength conversion, and light-splitting costs. They show since multicast routing is NP-hard, wavelength assignment can be solved more straightforwardly. The aforementioned optimal wavelength assignment algorithm appeared to have a significantly better performance, especially in Dense WDM networks, by minimizing the complexities of multicast routing and reducing the costs of communications. The techniques have applicability for much of the opto-electronics and fluorescent receiving wavelength conversion tasks.

Ramaswami et al. [24] discusses the routing of connections in reconfigurable optical networks using wavelength division multiplexing (WDM).A path and wavelength are assigned to every connection, ensuring no shared link has the same wavelength for different connections. The authors derive an upper bound on the traffic capacity (or lower bound on blocking probability) of any routing and wavelength assignment (RWA) algorithm. Although computationally intensive, this bound can be used to compare the performance of RWA algorithms for networks of moderate size. Simulation results show that simple shortest-path RWA (SP-RWA) performs close to this bound, with wavelength reuse increasing with network size and the number of wavelengths. Wavelength converters provide a 10–40% increase in reuse for small networks, and the results indicate that large optical networks can support multiple full-duplex connections per node with a reasonable number of wavelengths, even without converters.

Randhawa et al. [25] presents two static and three dynamic routing and wavelength assignment (RWA) algorithms whose main purpose is reducing blocking probability and maximizing network utilization. The static algorithms, SRWA3 and SRWA4, perform well with first-fit and most-used wavelength assignment strategies, achieving reduced blocking probability and complexity compared to existing algorithms.A model without weights is introduced for dynamic models, followed by three proposed algorithms including weight assignments, reducing probability of blocking further. Among the dynamic algorithms, the "less weight to maximum empty and nearest" approach (DRW3) gives the least probability of blocking for wavelength assignment schemes ,whether it be random, most-used, or least-used. The choice of wavelength assignment strategy impacting performance is also investigated by the authors, with discovery that different algorithms are better under specific strategies, making required careful selection to reduce blocking across the network.

Christodoulopoulos et al. [26] presents algorithms for the static routing and wavelength assignment (RWA) problem, focusing on minimizing the maximum requested wavelengths using linear programming (LP) relaxation. It introduces link and path formulations, along with a heuristic that splits the problem into two subproblems. The flow cost functions provide integer optimal solutions for many input instances and minimize total wavelengths used. A random perturbation technique increases the number of integer solutions, supplemented by iterative fixing and rounding methods for non-integer cases. Simulations show that these algorithms outperform typical min-max formulations, approximating integer linear programming (ILP) performance while significantly reducing execution time.

Azodolmolky et al. [27] extensively surveys the shift in optical networks from opaque and translucent approaches to all-optical (transparent) systems, where the situation regarding the integration of physical layer impairments (PLI) in routing and wavelength assignment (RWA) problems is brought to the fore. It categorizes impairments into linear and nonlinear effects and propounds algorithmic techniques, delineating beforehand verification of constraints post-lightpath selection and the later incorporation of PLI metrics into shortest path computations. They highlight the advantages of wavelength conversion and grooming in boosting optical performance while presenting the incorporation of PLI-RWA algorithms into control planes using Path Computation Element (PCE) models. It allows optimal path computation but faces challenges in scalability. The paper concludes that PLI-RWA algorithms are critical to the overall optimization approach in optical network design which aims to bring about comparable utilizations to opaque architectures while enjoying a reduction in operating cost and further invites research in ascertaining the accuracy of the impairment data and regenerator placement schemes.

Zhang et al. [28] presents a conceptual framework of multihop lightwave networks for high-speed packet transport with wavelength division multiplexing (WDM). This focus is primarily on the construction of scalable connection graphs that allow for a flexible wavelength assignment approach to accommodate the varying traffic patterns and configurations of networks. A heuristic algorithm takes the form of realizable optical connection graphs conforming to physical wavelength constraints, further subjected to routing evaluations. Simulation results show that the blocking performance of the obtained logical connection graph is nearly identical to that of a centralized switching system under varying parameter conditions, thus indicating that the optical network offers great relief in assisting user-to-user traffic flow. This paper is divided into network architecture, formulation of wavelength assignment, routing schemes, simulation results, and conclusions.

3 Methodology

This paper presents a simulation framework with a focus on wavelength division multiplexing (WDM) and dynamic resource allocation strategies, for evaluating the performance of single/multi-hop optical networks. Under diverse traffic conditions, the framework simulates various routing and wavelength assignment (RWA) algorithms to analyze their effectiveness in managing network resources.

3.1 System architecture

The proposed simulation framework serves as a sophisticated model for evaluating the performance of optical Wavelength Division Multiplexing (WDM) networks. These wavelength channels form the backbone of the optical WDM network that enables the high-capacity transmission of data and facilitates efficient communication. A physical and a virtual topology are used in the framework to structure the network. The physical topology explains the structural components, including nodes and fiber links, defining the layout of the physical network. On the other hand, virtual topology offers an abstraction layer which provides multi-hop communication, creating logical connections among the nodes for streamlined flow of data in an efficient manner.

Traffic in the network is simulated as flows between source and destination pairs, characterized by key parameters such as arrival time, bandwidth demand, and duration. To manage these flows, the simulator uses an event scheduler to keep track of arriving and departing traffic. A traffic generator replicates a variety of different traffic patterns to determine network behavior under various loads. Wavelength continuity is an important constraint in WDM networks. A lightpath should, therefore maintain the same wavelength over all links in its route. The framework allows for a comparison of RWA algorithms that determine optimal paths and provision wavelengths for flows of traffic. Resource allocation within the system is dynamic, making it adapt to the arrival and departure of traffic demands in real-time.

The framework also examines both single-hop and multi-hop grooming schemes. Single-hop grooming has traffic routed directly between source and destination nodes with a guaranteed lightpath for each flow. Although simple to implement, it is often resource-inefficient. In contrast, multi-hop grooming routes through intermediate nodes and allows the sharing of wavelength channels or the aggregation of flows within the network, thus increasing the ability to conserve the number of lightpaths. The above strategy improves spectral efficiency and reduces the blocking probabilities. Such grooming procedure is dependent on the RWA algorithm used, as different algorithms have priorities in objectives like hop count minimization, spectral efficiency maximization, or blocking traffic probability minimization.

To assess the performance of RWA algorithms, it makes use of a defined set of standard performance metrics. The metrics used include Maximum Blocking Probability (MBP), which measures the likelihood of some amount of traffic flow from being blocked; Allocated bandwidth refers to the dynamic assignment of a specific portion of the optical spectrum to a communication demand based on its data rate and quality requirements; and Jain's Fairness Index (JFI), used in the evaluation of fairness aspects of resource allocation among traffic flows. The framework helps to gain valuable insights into which RWA strategies best balance traffic demands while minimizing blocking with the optimal use of resources, by graphing and analyzing metrics across different traffic loads and network topologies.

The framework thus provides a robust platform to simulate and study WDM networks by integrating physical and virtual topologies, dynamic resource allocation, traffic grooming strategies, and comprehensive RWA algorithm analysis. It can produce crucial information to enhance the performance and resource utilization of the network under several diverse conditions, making it an important tool in the advancement of optical network design and optimizing the communication infrastructures in increasingly complex network environments.

3.2 Performance Metrics

The system measures the performance of the network using several key metrics:

Mean Blocking Rate: This metric represents the percentage of calls that are blocked due to insufficient resources (i.e., wavelengths or bandwidth). It is calculated as the ratio of blocked calls to the total number of calls, multiplied by 100.

$$MBR = \left(\frac{BlockedCalls}{TotalCalls}\right) \times 100 \tag{1}$$

Allocated bandwidth: In Elastic Optical Networks (EONs), allocated bandwidth refers to the dynamic assignment of a specific portion of the optical spectrum to a communication demand based on its data rate and quality requirements. EONs, as opposed to fixed-grid WDM, divides the spectrum into small frequency slots (e.g., 12.5 GHz) and assigns a suitable number of adjacent frequency slots that would match the traffic demand. This allocation is also affected by the modulation format, which determines spectral efficiency, and it includes guard bands to prevent interference. By changing bandwidth allocation in real time, EONs optimize spectrum usage, enhance scalability, and accommodate a variety of traffic demands efficiently.

Jain's Fairness Index (JFI): The JFI is used to measure the balance of blocking among all source-destination pairs. A JFI value around 1 indicates the network is well balanced where blocking is distributed among all pairs while a value nearer 0 indicates that some pairs experience relatively more blocking than others.

$$JFI = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2} \tag{2}$$

where xi represents the MBBR for each source-destination pair, and n is the total number of pairs. These performance metrics provide a comprehensive view of how efficiently the network manages its resources, particularly in terms of how fairly bandwidth is allocated and how often traffic demands are blocked.

3.3 Mathematical model

The mathematical model for the Adaptive Genetic Algorithm follows the metrics defined below:-
Fitness evaluation: The **fitness function** in the Adaptive Genetic RWA algorithm evaluates how well a solution satisfies the wavelength assignment and routing requirements for a given flow. It incorporates penalties for undesirable characteristics such as unavailable wavelengths and high link utilization, steering the optimization process toward better solutions and it is calculated as shown below.

$$F = \sum_{i=1}^{L} (P_i + U_i) \tag{3}$$

Mutation rate adjustment: The **mutation rate** defines the probability of altering the genetic makeup (wavelength assignment) of a solution. Mutation Rate Adjustment dynamically modifies this probability based on the diversity of the population and it is calculated mathematically like how it is shown below.

$$M = M_0 \cdot \left(1 - \frac{D}{P}\right) \tag{4}$$

Crossover: Crossover combines two parent solutions to generate an offspring by inheriting genes (wavelength assignments) from both parents. It is a key mechanism for exchanging information and generating better solutions. While crossing over, the best traits from both the parents are taken into consideration and hence the offspring will have the benefits of both while mitigating the losses of both.

$$O[i] = \{\, P_1[i], if random() < 0.5 P_2[i], otherwise \tag{5}$$

Mutation: Mutation introduces random alterations to a solution's genes (wavelength assignments) with a certain probability (mutation rate). It ensures that the adaptive genetic algorithm will have the best possible solutions after it explores a plethora of plausible solutions.

$$G[i] = \{\ randomnewwavelength, ifrandom() < MG[i], otherwise \tag{6}$$

RSA using Adaptive Genetic Algorithm
Input: Source node S (starting node of data flow), destination node D (ending node of data flow), total number of frequency slots F_s (available frequency slots in the network), bandwidth of request B_x (required bandwidth for the data flow).
Output: Allocated spectrum for the selected route.

1: Calculate k shortest routes from S to D using a shortest path algorithm (e.g., Dijkstra's) and add them to the set $P = \{L_{P1}, L_{P2}, \ldots, L_{Pk}\}$. *($P$ represents all potential routes)*

2: For each $L_{Pj} \in P$ *(iterate through each route to evaluate its feasibility)*
3: For $i \in [0, B_x]$ *(loop through frequency slots for the required bandwidth)*
4: Calculate i-th available frequency slot B_{ai}. *(B_{ai} represents the availability of the slot)*
5: If $B_{ai} - B_x \geq 0$ *(check if the slot can accommodate the bandwidth)*
6: $B_{ai} = B_x$ in set $B'(P)$ *(mark the slot as allocated in $B'(P)$)*
7: End If
8: End For *(end of frequency slot iteration)*
9: Set $B'(P_j) = \{B'(P_1), B'(P_2), \ldots, B'(P_j)\}$ *(list of available slots for route j).*

10: Select Min $\{B'(P_1), B'(P_2), \ldots, B'(P_j)\}$ to allocate in route L_{Pj}. *(choose the smallest available slot for allocation)*
If there are two minimum values, choose the lowest sequence number.

11: $u_j = B_{ai} - 1$ *(compute the residual slots after allocation).*
12: Calculate C_{ei} and set in $C_{ei}(P_j)$ *(compute spectrum completeness for the route).*

13: End For *(end of route iteration)*

14: $C_e(P_1), C_e(P_2), \ldots, C_e(P_k)$ *(set of spectrum completeness values for all routes).*
15: Select the route corresponding to $\max\{C_e(P_1), C_e(P_2), \ldots, C_e(P_k)\}$ to allo-

cate spectrum. *(choose the route with the best spectrum completeness)*

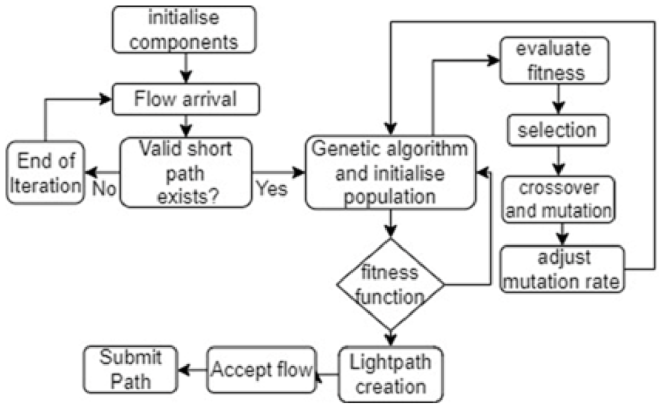

Fig. 1. Methodology

3.4 Simulation Parameters

NSFNET NSFNET, a pioneering high-speed backbone network developed in the late 1980s, serves as a foundational reference for our project due to its historical significance and technical structure. It had been designed to connect U.S. academic and research institutions, exchange data, and foster collaboration; it eventually modeled the international backbones. Decommissioned in 1995, the long-documented topology still provides an important benchmark for simulating and comparing network technologies. With NSFNET in our project, we are able to use its simplicity and controlled environment to drive algorithm studies while showing how a more modern elastic optical technology can enhance earlier network designs, increasing the history and technical depth of our research.

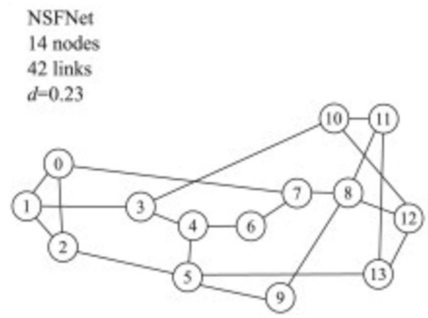

Fig. 2. NSFNET: 14 nodes 42 links network

Table 1. Network Parameters for nsfnet

Connection Management Scheme	**Distributed**
Topology	NSFNET
Number of Nodes	14
Number of Links	42
Link Weight	Distance in Km
Link Delay	1ms for 200km
Number of Wavelengths	16

EuroCore EuroCore, a high-capacity optical backbone network in Europe, is a crucial reference for our project due to its realistic and representative topology. It interconnects national and regional academic networks, supports large-scale research collaborations, and serves as a testbed to evaluate advanced optical technologies such as EONs. Hence, its complexity and scale provide a challenging environment to assess the performance and scalability of routing and resource allocation algorithms. This means that by including Eurocore in our project, we validate the practical applicability of our approach in addressing modern optical backbone demands while aligning with global advances in optical networking.

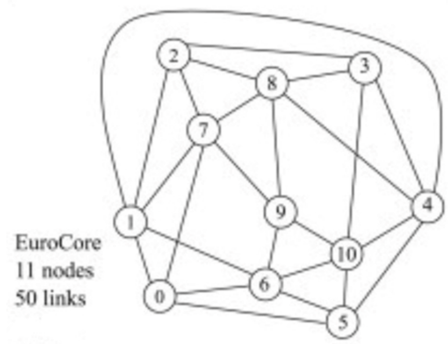

Fig. 3. Eurocore: 11 Nodes 50 links network

Table 2. Network parameters for eurocore

Connection Management Scheme	**Distributed**
Topology	EuroCore
Number of Nodes	11
Number of Links	50
Link Weight	Distance in Km
Link Delay	1ms for 200km
Number of Wavelengths	16

Max load	1000
Min load	300

Table 3. Assumptions

4 Simulation Results

Parameter	**Value**
Population Size	80
Generations	70
Mutation Rate	0.1

Table 4. Genetic Algorithm Parameters

The Genetic algorithm is being compared with Far-FF (Farther-First-Fit) and Far-LL (Farther-Least-Loaded) in NSFNET and Eurocore

FAR-FF (Farther-First-Fit): This algorithm prioritizes routing flows over longer paths first, reducing the likelihood of bottlenecks forming on shorter paths. It assigns wavelengths using the First-Fit strategy, which selects the first available wavelength for all links on the path. This approach is simple and efficient but may not always lead to optimal resource utilization.

FAR-LL (Farther-Least-Loaded): This algorithm also prioritizes longer paths but improves resource management by selecting the least-loaded wavelength for each link. By considering wavelength usage, it achieves better load balancing, which can reduce blocking probabilities and improve network performance, especially under high traffic loads. NSFNET :-

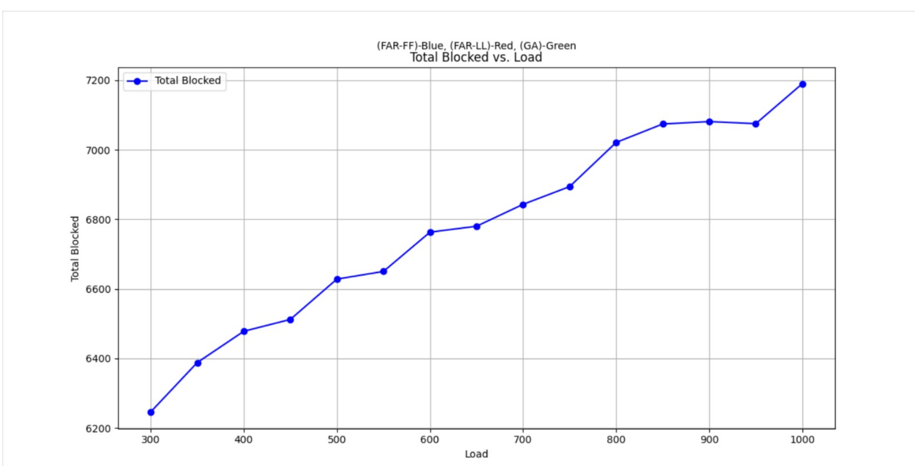

Fig. 4. FAR-LL

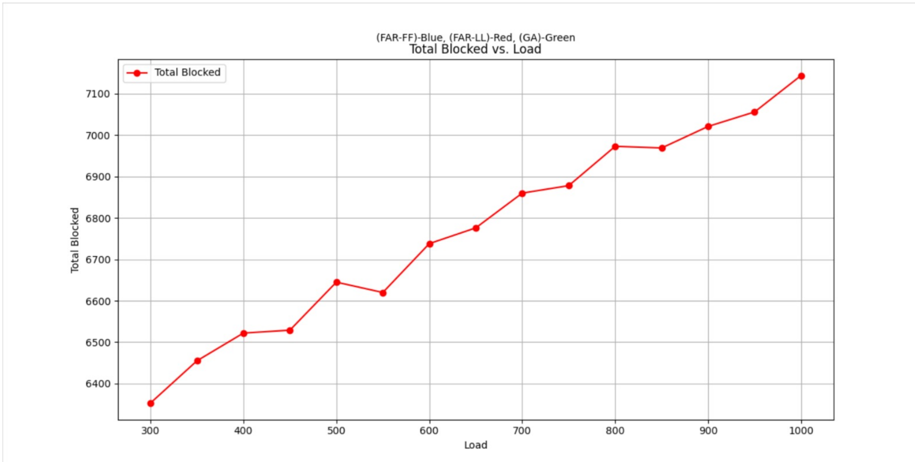

Fig. 5. Far-FF

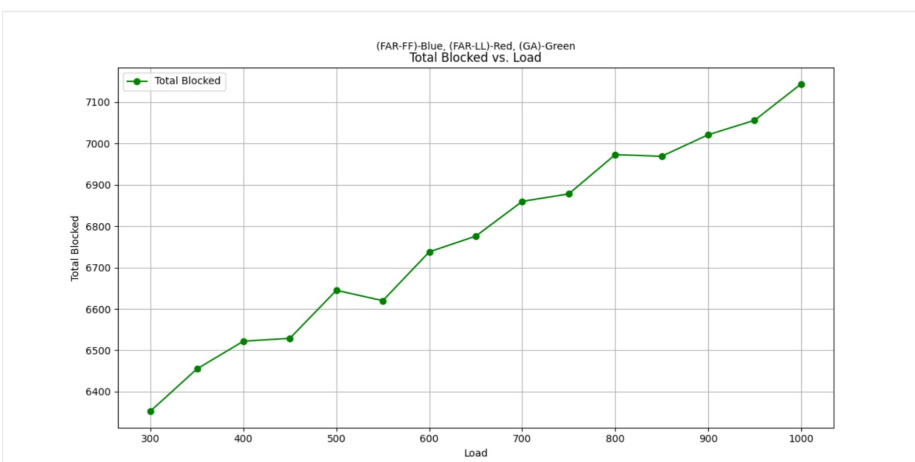

Fig. 6. Genetic Algorithm

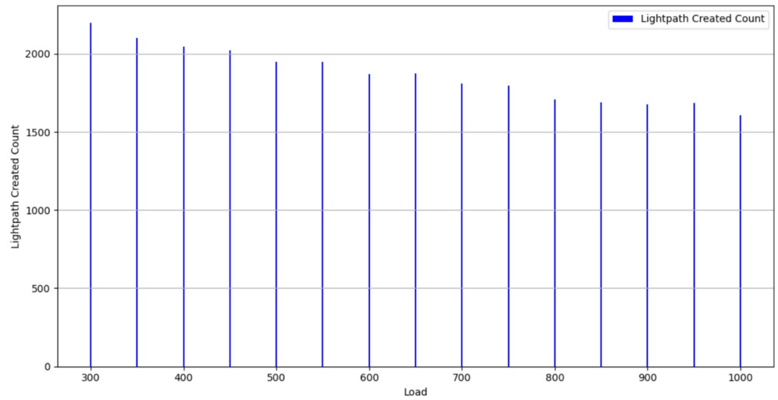

Fig. 7. Amount of light paths created for FAR-LL

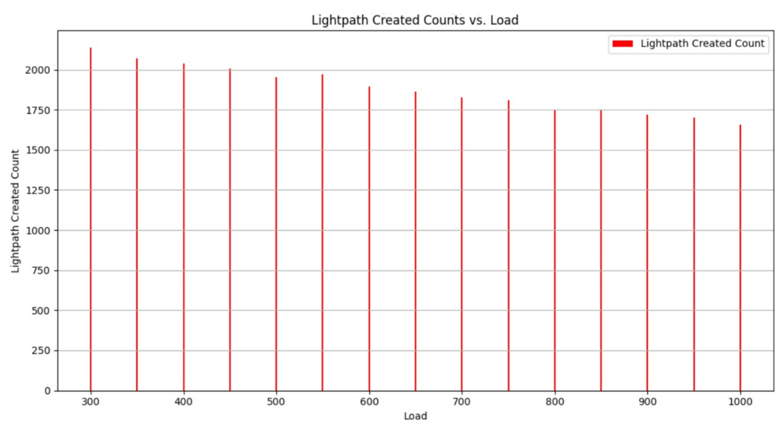

Fig. 8. Amount of light paths created for FAR-FF

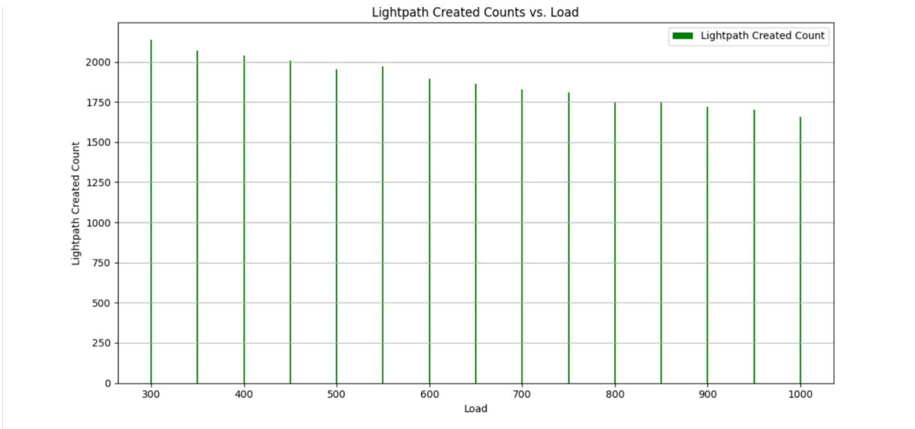

Fig. 9. Amount of light paths created for Genetic Algorithm

Eurocore :-

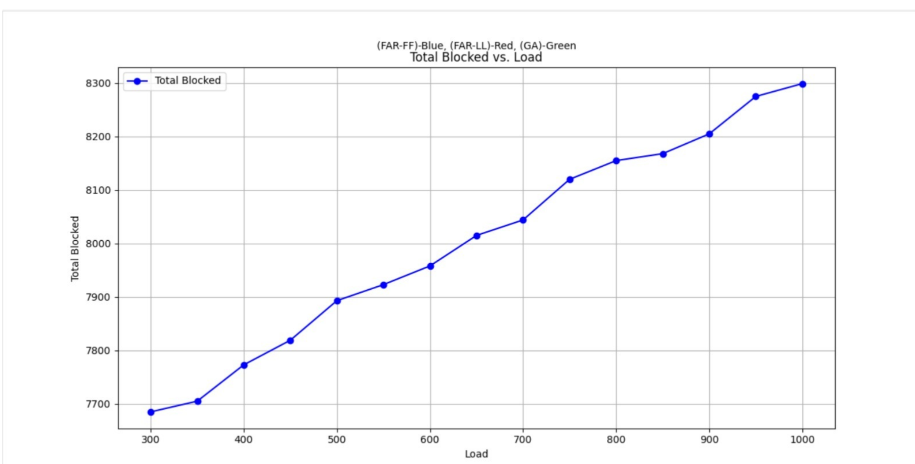

Fig. 10. FAR-LL

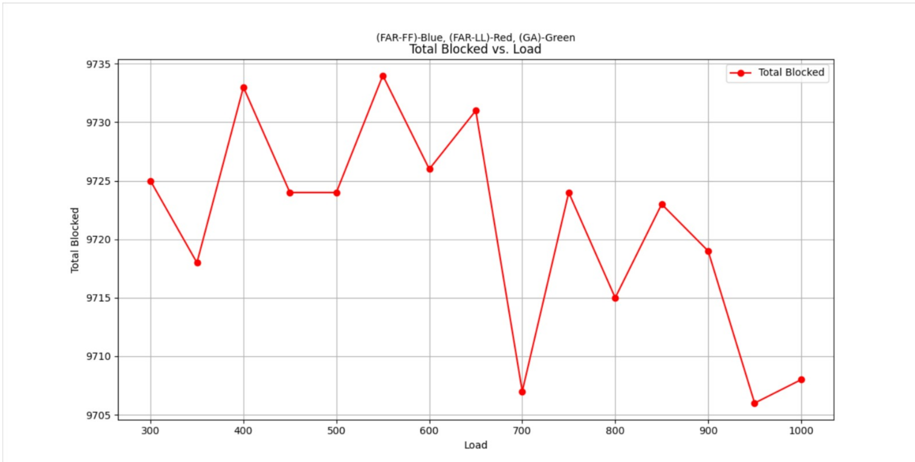

Fig. 11. FAR-FF

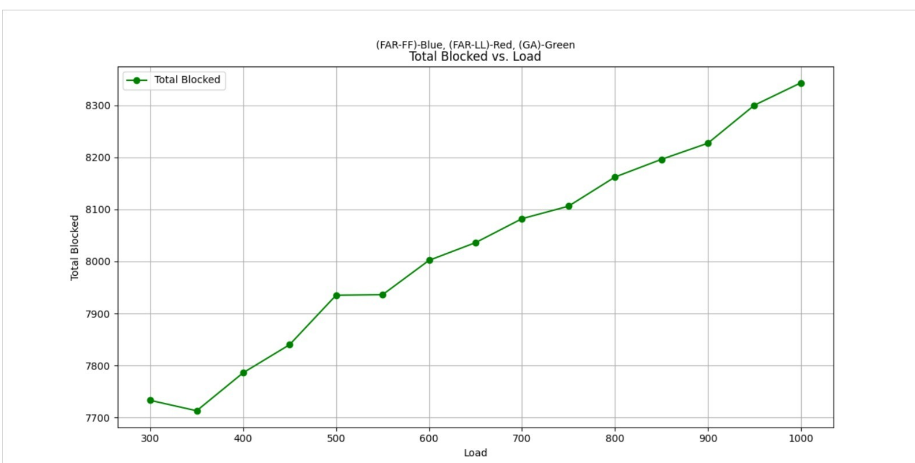

Fig. 12. Genetic Algorithm

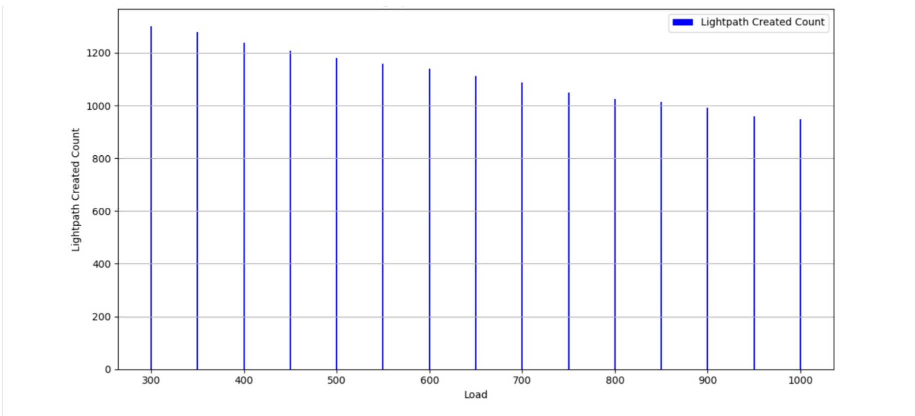

Fig. 13. Amount of light paths created for FAR-LL

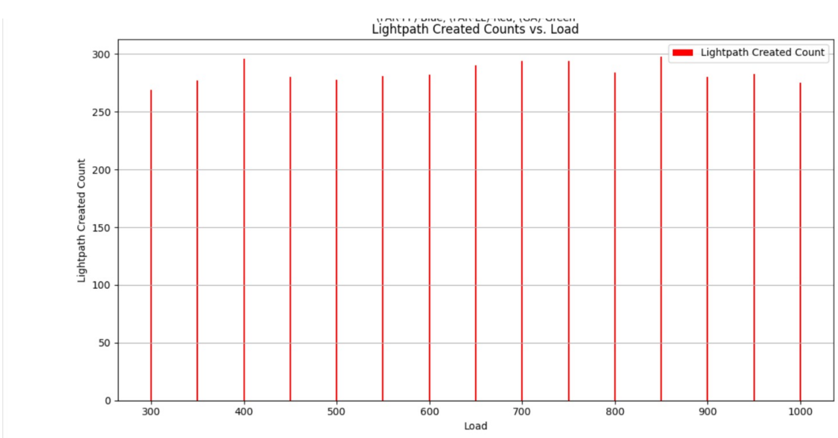

Fig. 14. Amount of light paths created for FAR-FF

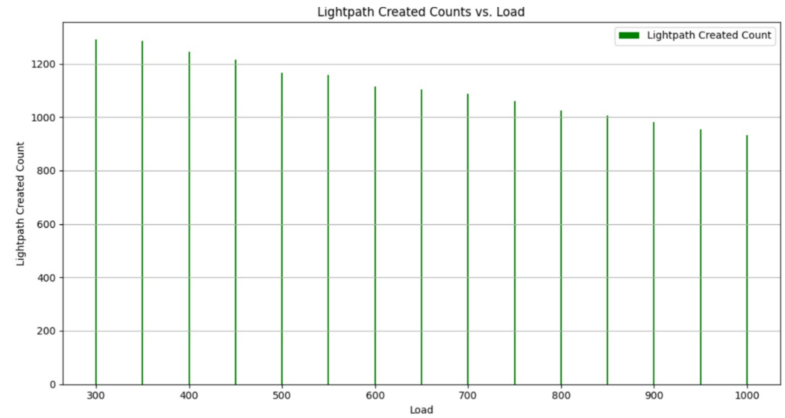

Fig. 15. Amount of light paths created for Genetic

Table 5. Average JFI Index

Algorithm	**NSFNet**	**EuroCore**
FAR-LL	0.851	0.997
FAR-FF	0.836	0.835
Genetic	0.857	0.827

The genetic algorithm, configured with the parameters outlined in Table 4 and based on the specified mathematical model, demonstrated superior performance in terms of JFI (2) on the NSFNET network compared to other algorithms. However, it underperformed on the EuroCore network. Regarding blocking probability, its performance showed slight improvement, but it did not deliver any notable cost advantages relative to the other algorithms.

5 Conclusion and Future Scope

In this research, we were able to build a novel algorithm which is inspired from the genetic algorithm. Through this algorithm, we were able to show similar results compared to the traditional existing algorithms like FAR-FF and FAR-LL, this acknowledges the potential this algorithm has while solving the RWA(Routing and wavelength Assignment) problem.This can easily address the demands of bandwidth made by various systems present in networks in the current world, and it also opens up a path to match the future requirements as the network grows.
Efficient delivery of the requested amount of bandwidth is what most of the companies work on to deliver and this proposed method improves the overall

network throughput, reduces flow blocking probabilities and maintains fairness during resource distribution.
This research can be taken up in future and can be induced with optimization of parameters for the genetic algorithm and can be made dynamic with the induction of machine learning, this will allow the algorithm to learn from historical data and further optimize routing.

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