Engineering and Technology Journal e-ISSN: 2456-3358

Volume 11 Issue 01 January-2026, Page No.-8605-8613

DOI: 10.47191/etj/v11i01.22, I.F. – 8.482

Advanced Multi-Protocol Label Switching (MPLS)-Enabled Networks: A Survey of Emerging Approaches Via Traffic Engineering

Yash Muni

Infogain Corporation

ABSTRACT: An in-depth analysis of MPLS-based systems, highlighting the progress in Traffic Engineering (TE) and its recent developments that address the current flow of modern data. The scalability and flexibility of MPLS play a decisive role in data routing because it uses labels for the simplification of forwarding and the increase of network efficiency. Despite MPLS-TE being successful for traffic management, further efforts on data and application needs require the introduction of more advanced solutions. This study looks at how new technologies, specifically Software-Defined Networking (SDN), Segment Routing (SR), and Artificial Intelligence (AI), are shape-shifting MPLS-TE to being more elastic, efficient and capable of auto-traffic control. These technologies address the shortcomings experienced by legacy approaches, by preparing networks to manage resources better, offer better Quality of Service (QoS), and adapt quickly to changes in demand. By exemplifying the usage of these cutting-edge tools, the paper provides excellent indications of the future of MPLS-TE and its ability to address the needs of next-generation networks.

KEYWORDS: MPLS, Traffic Engineering, Multi-Protocol Label Switching, Constraint-Based Routing, RSVP-TE, Segment Routing

I. INTRODUCTION

Digital communication has evolved at unprecedented speed and network infrastructures should always guarantee fast, reliable and efficient data transfer. MPLS is the core of meeting these needs in the form of flexible and extensible solutions for routing data effectively [1]. With the use of labels for forwarding decisions, MPLS speeds up the packet transmission time, reduces latency and improves general network efficiency. MPLS has flexibility with any protocol, making it capable of seamlessly adapting itself to a variety of networks thereby keeping it relevant in today's set up of networking.

Traffic Engineering implementation in MPLS networks is the game-changer that optimizes data traffic without compromising resources management and QoS [2][3]. Established Traffic Engineering methods like Constraint-Based Routing (CBR), and Resource Reservation Protocol-Traffic Engineering have played a significant role in managing network traffic while considering multiple constraints and reserving necessary resources along the path [4][5]. These approaches are the foundation for the consistent and high-performance operation of networks, essential to support important applications and services.

MPLS-based traffic engineering has proved to be a viable proposition for the reduction of IP network congestion. The main concept is to steer traffic flows away from congestion and hot areas in the network by using MPLS's route pinning facility [6]. The traffic engineering of MPLS-based VPNs with many service classes in a centralized environment is examined in this study.

In the last ten years, MPLS has emerged as the preferred transport technology for packet-based core networks [7][8]. The creation of many strategies to raise the degree of network availability, dependability, and optimality has been made possible by MPLS technology. To optimize resource utilisation and network performance, traffic engineers also employ MPLS to regulate traffic flows over networks [9][10]. Traffic Engineering Fast Reroute (MPLS TE-FRR) and Differ-aware Traffic Engineering (MPLS DS-TE) are often used in conjunction with MPLS Traffic Engineering (MPLS TE). As stated, MPLS is subject to QoS capabilities via the Differentiated Services architecture [11]. An MPLS Label Stack Entry (LSE) uses the three-bit Traffic Class (TC) field to differentiate between various kinds of traffic.

A. *Structure of the Paper*

The paper is structured as follows: Section II explains MPLS and Traffic Engineering fundamentals. Section III explores MPLS-TE architectures and frameworks. Section IV discusses emerging approaches like SDN and AI in MPLS-TE. Section V provides a literature review on recent advancements and challenges.

II. FUNDAMENTALS OF MPLS AND TRAFFIC ENGINEERING

Two distinct kinds of routers are used to carry out MPLS activities. In a MPLS network, LERs are located at the "edge" and usually have connections to other networks. Layer 2 networks (e.g., ATM, Frame Relay, or Ethernet) and MPLS core networks are connected by LERs, which also route traffic. A label is appended to packets received by LERs from the layer 2 network before that are forwarded into the MPLS core network. Based on the configuration of other routers, a packet will take a particular route, known as a LSP, from one LER to another[12][13]. This route is determined by the subsequent interpretation of the packet based on its label. After receiving a packet from the MPLS network, the LER removes the label and sends it to the appropriate layer 2 network.

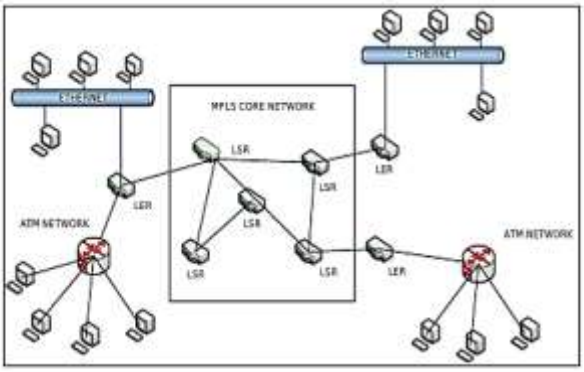

Fig. 1.MPLS Network

A regular MPLS network. Figure 1 shows the MPLS network and many layer 2 networks to which each LER is linked. Although Frame Relay is not included in the diagram, MPLS does support Ethernet and ATM networks [14]. LSRs are linked to either LERs or other LSRs [15]. Layer 2 networks send packets to LERs, which in turn send them to LSRs, and finally to an egress LER, which sends them to yet another layer 2 network.

A. Basic Concepts in MPLS Traffic Engineering (MPLS-TE)

MPLS-TE enhances IP routing by enabling traffic to be directed along explicitly defined paths, optimizing resource utilization and ensuring Quality of Service (QoS) [16]. Unlike traditional routing, which relies on destination-based shortest paths, MPLS-TE supports path customization and efficient traffic distribution across the network.

1) Label Switched Paths (LSPs)

LSPs are unidirectional paths established using protocols like RSVP-TE, allowing packets to traverse a sequence of label-based hops [17]. Until such times, defining these routes in advance will help to reduce congestion and increase efficiency.

2) Explicit Route Objects (EROs)

Using EROs allows ingress routers to define precise routing paths for LSPs with enhanced control as compared to default routing functions.

3) Constraint-Based Routing

To guarantee appropriate paths for use, computations consider constraints such as bandwidth, delay, or policy, only to choose qualified routes for traffic forwarding.

4) Trunks and Class Types

Traffic that demands similar Quality of Service (QoS) is grouped together in trunks and divided by using Class Types (CTs), which affords different resource management.

5) Administrative Groups and Link Attributes

Network links are labelled with attributes like bandwidth, delay, and colors that make them easy for policy-based and performance-driven path selection [18].

6) Path Selection and Setup

Ingress routers use procedures such as Constrained Shortest Path First (CSPF) to calculate valid paths whereas RSVP-TE governs signalling and network resource reservations.

7) Forwarding Equivalence Classes (FECs)

FECs are established to aggregate packets that have the same requirement on handling. A label binds FECs to LSPs, which will enable effective and consistent packet forwarding.

B. Label Distribution Protocols (e.g., LDP, RSVP-TE)

In MPLS-enabled networks, label distribution protocols are responsible for assigning and disseminating labels that direct packet forwarding along Label Switched Paths (LSPs) [19][20]. The protocols act as the control plane of MPLS, which build and maintain forwarding tables to establish appropriate label-route correspondences. The key label distribution protocols used in MPLS networks is LDP and RSVP-TE.

1) Label Distribution Protocol (LDP)

RFC 5036 defines LDP, a standard signalling protocol that is used to create LSPs using pre-existing routing data. It functions on a hop-by-hop basis[21], where each router independently chooses the destination's next hop and labels it appropriately.

Key Features of LDP

- **Simplicity:** Automatically builds LSPs using the underlying Interior Gateway Protocol (IGP) routes.
- **Scalability:** Extremely suitable for large scale deployments with little configuration tuning [22].
- **Lack of Traffic Engineering Support:** LDP does not support explicit routing or resource reservation, limiting its use in traffic-engineered applications.
- **Best Effort Behaviour:** The system does not possess the ability to guarantee QoS or reserve bandwidth.

2) Resource Reservation Protocol with Traffic Engineering (RSVP-TE)

RSVP-TE, defined in RFC 3209, is an enhancement of the original RSVP protocol to support MPLS-TE. It makes it possible to reserve resources at various points along the route and to build LSPs with specified routing.

Key Features of RSVP-TE

- **Explicit Routing:** Allows ingress routers to define the entire path (via Explicit Route Objects, or EROs).
- **Constraint-Based Routing:** Integrates with path computation algorithms like CSPF to meet bandwidth, latency, or policy constraints [23].
- **Resource Reservation:** Supports bandwidth guarantees by reserving link resources during path setup.
- **Soft State Maintenance:** Uses periodic refresh messages to maintain state, which can increase signalling overhead. Table I provides the comparison and use cases of LDP and RSVP-TE below:

TABLE I. COMPARISON AND USE CASES

Feature	LDP	RSVP-TE
Path Type	Hop-by-hop	Explicit routing
Traffic Engineering	No	Yes
Bandwidth Reservation	No	Yes
Complexity	Low	Higher
Suitable Use Cases	Basic MPLS forwarding	MPLS-TE, QoS, and service guarantees

III. ARCHITECTURES AND FRAMEWORKS FOR ADVANCED MPLS-TE

Services provided by MPLS networks include the categorization and definition of IP data packets on the router or input node, assigning each packet a local relevant identifier (a tag) and either a brief or a set length. The router receives the packets based on the categorisation of the tag. Furthermore, without using network layer addresses, the modified router or node uses these markers to distribute or send IP data packets throughout the network[24][25]. The MPLS network in this design must finish IP data packet routing by applying the mark in the MPLS header. This IP packet needs to have the MPLS header inserted into it before it can be transported in the MPLS domain [26][27]. The MPLS header is included in the native tag region of protocols that employ data-link layer switching, such as ATM. If the Layer 2 technology rejects the native tag area, the MPLS header needs to be placed between the Layer 2 and Layer 3 TCP/IP connection headers. Figure 2 depicts the MPLS architecture:

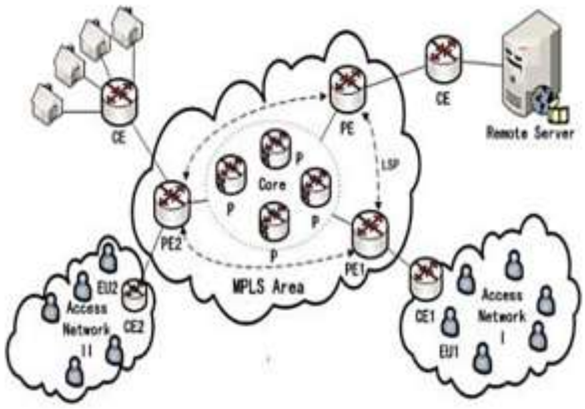

Fig. 2.MPLS Architecture

An MPLS network connecting multiple customer sites through a core of provider (P) and provider edge (PE) routers. Customer edge (CE) devices link user networks (EU1, EU2) to the MPLS area, where traffic is forwarded along Label Switched Paths (LSPs).

A. Centralized vs Distributed TE Architectures

The MPLS-TE Control approaches to Path Computation and Network Control can be stated in two broad methodologies; Centralized and Distributed architectures [28]. Centralized TE utilizes a global controller or the Path Computation Element (PCE), which requires full knowledge of the network in order to find the appropriate resource and configure an LSP, but it is a scalability problem and a single point of failure [29][30]. In contrast to the distributed TE, each router is capable of independently making its TE decisions using local as well as the overall topology information resulting in higher level of robustness and flexibility while controlling for the global system performance that might be slightly less optimal [31]. There are blended CT approaches that integrate a centralized control point with distributed deployment to ensure the benefits of both.

B. Software-Defined Networking (SDN) Integration

The integration of SDN in MPLS-TE introduces more centralized control and the ability to implement programmatic network paths, and the dynamic operational control of LSPs. SDN controllers can use protocols like PCEP, and BGP-LS to monitor the topology and the traffic and in a similar manner calculate paths on flies [32][33]. This improves real-time traffic optimization, quicker restoration of the network and improved compliance to the service level agreements, and works well with multiple vendor and multiple domain environment[34]. The specific characteristics of SDN makes it well suited for the improvement and extension of the traditional enterprise applications of MPLS-TE.

C. Segment Routing in MPLS-Enabled Networks

Segment Routing (SR), especially SR-MPLS, builds upon MPLS-TE and encodes the routing instructions as segments within the packet headers to eliminate the signalling needs like RSVP-TE, which in turn reduces per-flow state in the network. This reduces complexity, brings modularity, and helps in the deployment of newer features such as network slicing, service chaining and fast reroute [35][36]. SR in turn can rather successfully complement or replace MPLS-TE through integration with SDN controllers for centralized computation and distribution of segment lists for accurate traffic rerouting.

D. Hierarchical Traffic Engineering Models

HTE models intake TE at scale while partitioning the network into subregions with autonomous control and a Master node that controls the path setup process. In each domain, the standard TE protocols are responsible for traffic management at the local level, whilst the inter-domain problem is solved at the higher level by means of abstractions and multiple PCEs [37][38]. It makes it easier in terms of scalability, and more specifically it goes a long way in explaining how resources can be partitioned and where it is that policies can be enforced in multi domain and multi-layer networks. HTE is particularly most applicable in the large service providers where there is central control of the entire topology.

IV. EMERGING APPROACHES IN MPLS TRAFFIC ENGINEERING

The scalability, flexibility, and efficiency of classic traffic engineering (TE) approaches are problems as MPLS networks change to meet the increasing needs of contemporary data traffic. To address these issues, several emerging and advanced approaches have been developed. These methods leverage new technologies like Software-Defined Networking, Machine Learning, Segment Routing and Big Data analytics to enhance the capabilities of MPLS-based TE[39].

A. Software-Defined Networking (SDN)-Based TE in MPLS

The programmability and adaptability of SDNs are driving their rise to prominence. There is now a physical separation between the data plane and the control plane, making it much easier to administer and innovate the network via programming[40]. This feature enhances network agility and enables local providers to successfully conduct provisioning and monitoring [41]. All forwarding devices are managed by a single, centralized controller; networks too complicated to maintain might be divided into many controllers. Controlling the data flow over the network and giving network providers flexibility are the primary objectives of SDN[42]. The procedure allows for the execution of any traffic policy or TE with complete flexibility, instead of using the same scheme offered by suppliers[43]. Typical MPLS network traffic is quite dynamic and subject to congestion at any given moment. Because of the inadequacy of portraying traffic variations and the substantial measurement errors that may occur with a single traffic matrix, optimizing TE across only that matrix may have limits, particularly when large numbers of applications are routed via the network [44][45]. Network optimization and quality of service assurances are further complicated by the sheer size of today's networks. Full network optimization is possible with MPLS-TE and SDN integration.

B. Segment Routing (SR)

Source routing, in which packets include encoded information about the selected route, is the basis of Segment Routing, a routing system. Nodes obey the instructions in these segments, which are shown as a stack [46][47]. These segments may denote anything from the internal workings of a single device to the overall architecture of the whole network.

The SR-TE architecture plans the network's matching segment list to direct traffic down the SR route based on the operator's purpose expressed in an ordered list of segments [48][49]. An integral part of SR-TE is the segment list. As a result, this part gives an in-depth review of SR-TE focusing on two important parts: instantiating the segment list and computing the segment list [50]. It began with a synopsis of the SR Policy, a key framework for instantiating segment lists, and then it emphasized a number of significant SR-TE algorithms for computing segment lists. Along with appropriate strategies to tackle the obstacles, it also summaries the benefits.

C. Multi-Domain and Inter-AS Traffic Engineering

Traffic Engineering in MPLS-enabled networks focuses on efficiently managing traffic across multiple administrative boundaries while maintaining end-to-end performance guarantees. Hierarchical Traffic Engineering (TE) solutions are often employed to abstract lower-layer domain details and simplify inter-domain coordination, allowing for scalable and manageable TE in large networks [51]. The Path Computation Element (PCE), a crucial part of this design, is in charge of determining the best routes across domains based on network topology, restrictions, and regulations. The functioning of PCEs crosses the boundaries of centralized and distributed models; consequently, PCEs are critical for taking care of path computation in difficult multi-domain environments [52][53]. However, the objective of facilitating ease of interoperability across several domains that is capable of harnessing disparate routing protocols, policies, or hardware, raises critical points especially regarding the topic of standardization, security, and the costs of interfacing across them.

D. Machine Learning and AI-Based Techniques

The utilisation of ML and AI into the MPLS TE is working towards better network performance and increased adaptability. These technologies through complex algorithms offer the ability to predict traffic trends and optimize routes based on these trends, thus allowing the networks to vary according to changing needs in real time [54][55]. For example, ML algorithms may be used to analyze both historical and current traffic data to predict bottleneck issues and becoming possible to make proactive adjustments to routing strategies and to reduce latency and increase efficiency. Bernárdez et al. paper proposed a MAGNNETO instead, a distributed ML approach that integrates Graph Neural Networks with Multi-Agent Reinforcement Learning[56][57]. The advancement in this sphere suggests that ML and AI adoption in MPLS TE may lead to self-aware, self-adaptive that can perform well in managing modern data traffic.

V. LITERATURE REVIEW

This section reviews key studies on advanced Traffic Engineering in MPLS-enabled networks, covering both traditional and emerging approaches. Table II summarizes the core methods, findings, and challenges.

Nedhunuri et al. (2024) describes how the network environment configuration and architecture of seven interconnected routers can be used to encourage every possible type of traffic pattern and redundancy. Then the extensive simulation and analysis is performed to confirm the enhanced performance due to MPLS TE. Then, by measuring criteria such as latency, bandwidth usage, and general Quality of Service (QoS), it is concluded that with the use of MPLS TE, a significant decrease in congestion and effective management of data flow can be achieved, impacting both the end hosts in the network. The implementation difficulties and limitations are discussed, which are in the form of complexity in configuration and interoperability compared with other existing routing protocols [58].

Jiang and Sakamoto (2023) It emphasises on Software-Defined Networking (SDN) networks and Segment Routing Traffic Engineering (SR-TE). It proposes a heuristic Pruned Landmark Labelling (hPLL) method that dynamically selects the best Landmark as the intermediate node for each traffic flow.

This reduces the Maximum Link Utilization (MLU) in the network with restricted Segment Identifiers (SIDs), making it more suitable for large-scale SR operator networks. Through a series of experiments. However, basic route control typically selects only one of these paths, leading to potential link congestion. For this reason, Traffic Engineering (TE) utilizing Multi-Protocol Label Switching (MPLS) and Segment Routing (SR) have been developed to enable the selection of routes other than the shortest path [59].

Alja' afreh, Obaidat and Alouneh (2022) starting with a quick rundown on MPLS, constraint-based routing, and the OSPF protocol to set the stage for traffic engineering. By using MPLS, the network is able to provide a seamless flow of traffic. In Multiprotocol Label Switching (MPLS), the Label Switch Router (LSR) establishes label switched paths (LSPs) using signalling protocols such as Resource Reservation Protocol (RSVP), Label Distribution Protocol (LDP), and Border Gateway Protocol (BGP). LSPs only take predetermined routes rather than the fastest one. Managing data traffic on the chip system around The network is just one of the several important uses for MPLS technology, which also enables high-performance forwarding architecture. This study presents the findings of three different topologies' simulations. Additionally, it address the possible advantages and drawbacks of each architecture [60].

Monika, Singh and Wason (2022) dynamic users are suggested for a GMPLS network. The suggested GMPLS optical networks have since been equipped with various methods for distributing bandwidth. There are algorithms like Minimum Execution Time (MET), Minimum Completion Time (MCT), and Opportunistic Load Balancing (OLB). Although the algorithms in question are extensively used, they have not yet been used to Generalised Multi-Protocol Label Switched optical networks; this highlights the originality of the present effort. They examine and contrast the network performance of each method. The findings show that MET decreases the latency to less than 1ms and the blockage probability to less than 0.1% [61].

Singh, Kumar and Shushrutha (2021) a straightforward, automated, and extensible framework for designing network traffic flows with explicit and dynamic route rules is provided by Segment Routing - Traffic Engineering (SR- TE). The Cisco Modelling Labs used CISCO IOS-XRv routers to construct the topology. The topology is also compatible with the SR-PCE, which is an IOS-XRv-based path computation element. SR PCE, whether in a decentralized or centralized control setting, offers multi-domain path disjoints and the ability to compute scalable multi-domain SR optimized paths. This enables complete command of the traffic flow [62].

Aurel et al. (2022) to study MPLS networks that operate at high speeds, outlining the fundamentals of label switching, potential optimization methods for alternative routing, issues with error recovery, and ways to construct virtual private networks. The primary objective of MPLS is to combine IP traffic with the rising availability of high-speed optical networks. Conversely, QoS encompasses more than just traffic speed; the capacity to swiftly recover from errors is another critical component. Consequently, optimizing network bandwidth utilization without using too crucial information is the primary objective of this paper [63]

TABLE II. COMPARATIVE SUMMARY OF LITERATURE REVIEW BASED ON TRAFFIC ENGINEERING APPROACHES IN MPLS-ENABLED NETWORKS

Reference	Study On	Approach	Key Findings	Challenges	Future Directions
Nedhunuri et al. (2024)	MPLS Traffic Engineering (TE) in a network with 7 interconnected routers	Simulation-based performance analysis using MPLS TE	MPLS TE improves QoS, reduces congestion, and manages traffic efficiently	Complexity in network configuration	Improve configuration automation, reduce complexity, and enhance interoperability with non-MPLS protocols for broader adoption.
Jiang and Sakamoto, (2023)	Segment Routing Traffic Engineering (SR-TE) in SDN	Heuristic Pruned Landmark Labeling (hPLL) method to minimize MLU	hPLL outperforms traditional routing; better scalability for large SR networks	Handling multiple shortest paths and load balancing	Develop advanced algorithms that further reduce MLU and extend scalability in SR networks under strict SID limitations.
Alja'afreh, Obaidat and Alouneh, (2022)	MPLS, constraint-based routing and OSPF	Review of LSRs, signaling protocols, and LSPs with simulation of 3 topologies	MPLS enables smooth traffic flow via LSPs and enhances performance	Design complexity and protocol integration	Explore integration with emerging technologies like IoT and edge computing to enhance TE adaptability and dynamic flow control.

Monika, Singh and Wason, (2022)	Bandwidth allocation in GMPLS optical networks	Implementation of MET, MCT, OLB algorithms on GMPLS network	MET minimizes blocking probability (<0.1%) and latency (<1ms)	Dynamic user traffic and algorithm efficiency	Extend bandwidth optimization algorithms for real-time, dynamic optical traffic scenarios; test under hybrid (wired/wireless) GMPLS networks.
Singh, Kumar and Shushrutha, (2021)	SR-TE with CISCO IOS-XRv routers	Implementation of SR-PCE in Cisco Modeling Labs	Full control of traffic, scalable SR path computation across domains	Multi-domain optimization complexity	Improve multi-domain scalability and real-time SR-PCE coordination with AI-driven traffic prediction and path selection models.
Aurel et al. (2022)	MPLS for high-speed and QoS-sensitive networks	Review of MPLS routing, optimization, error recovery	Bandwidth optimization and QoS assurance in optical MPLS networks	Error recovery and integration with VPNs	Enhance error recovery mechanisms and bandwidth optimization using machine learning and integrate MPLS more tightly with optical core networks.

VI. CONCLUSION AND FUTURE WORK

The major issues and cutting-edge developments in Multi-Protocol Label Switching (MPLS) networks with an emphasis on Traffic Engineering (TE) advancements. Standard MPLS-TE methods played a key role in network performance and capacity management, but the changing complexity of contemporary applications calls for a new set of solutions. The introduction of Software-Defined Networking (SDN), Segment Routing (SR) and Artificial Intelligence (AI) has demonstrated the ability to transform MPLS-TE to enable greater flexibility, adaptability and real-time optimization. These developments provide a foundation for a better intelligent and self-automated network management, allowing the network to self-adjust under different unseen traffic patterns and service demands. The challenges that underlie MPLS TE are quite pronounced and include the complexities of large and dynamic networks as well as the assurance of interoperability of networks with different technologies and domains. There is a need for further investigation to improve the linkage of AI and ML for the MPLS-TE allowing better forecasting and dynamic routing solutions. It is also critical that it develop the MPLS-TE interoperability with new architectures, especially 5G and make MPLS remain a significant enabler in the next generation environment. Deployment of new methods including hierarchical traffic engineering, multi-domain management, and real-time optimization algorithms is likely to improve network scalability and efficiency dramatically.

REFERENCES

1. D. O. Awduche and B. Jabbari, “Internet Traffic Engineering using Multi-Protocol Label Switching (MPLS),” *Comput. Networks*, vol. 40, no. 1, pp. 111–129, Sep. 2002, doi:10.1016/S1389-1286(02)00269-4.
2. S. Tyagi, J. Xie, and R. Andrews, “E-VAN : Enhanced Variational AutoEncoder Network for Mitigating Gender Bias in Static Word Embeddings,” in *Proceedings of the 2022 6th International Conference on Natural Language Processing and Information Retrieval*, 2022, pp. 57–64. doi: 10.1145/3582768.3582804.
3. V. M. L. G. Nerella, K. K. Sharma, S. Mahavratayajula, and H. Janardhanan, “A Machine Learning Framework for Cyber Risk Assessment in Cloud-Hosted Critical Data Infrastructure,” *J. Inf. Syst. Eng. Manag.*, vol. 10, no. 4, pp. 2409–2421, 2025, doi: 10.52783/jisem.v10i4.12804.
4. B. C. Isaak and R. Planning, “A Comparison of Approaches for Traffic Engineering in IP and MPLS Networks,” pp. 142–155, 2011, doi: 10.48550/arXiv.1608.03770.
5. S. B. Karri, C. M. Penugonda, S. Karanam, M. Tajammul, S. Rayankula, and P. Vankadara, “Enhancing Cloud-Native Applications: A Comparative Study of Java-To-Go Micro Services Migration,” *Int. Trans. Electr. Eng. Comput. Sci.*, vol. 4, no. 1, pp. 1–12, Apr. 2025, doi: 10.62760/iteecs.4.1.2025.127.
6. C. T. Chou, “Traffic Engineering for MPLS-Based Virtual Private Networks,” *Comput. Networks*, vol. 44, no. 3, pp. 319–333, 2004, doi: 10.1016/j.comnet.2003.10.001.
7. K. Rajchandar, M. Ramesh, A. Tyagi, S. Prabhu, D. S. Babu, and A. Roniboss, “Edge Computing in Network-based Systems: Enhancing Latency-Sensitive Applications,” in *2024 7th International Conference on Contemporary Computing and Informatics (IC3I)*, IEEE, Sep. 2024, pp. 462–467. doi: 10.1109/IC3I61595.2024.10828607.
8. G. Maddali, “Enhancing Database Architectures with Artificial Intelligence (AI),” *Int. J. Sci. Res. Sci.*

Technol., vol. 12, no. 3, pp. 296–308, May 2025, doi: 10.32628/IJSRST2512331.

9. I. Ramadaa, J. Ozegovic, and V. Pekic, "Network performance monitoring within MPLS traffic engineering enabled networks," in *2015 23rd International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, IEEE, Sep. 2015, pp. 315–319. doi: 10.1109/SOFTCOM.2015.7314107.
10. S. Narang and G. K. V, "Next-Generation Cloud Security: A Review of the Constraints and Strategies in Serverless Computing," *Int. J. Res. Anal. Rev.*, vol. 12, no. 3, 2025, doi: 10.56975/ijrar.v12i3.319048.
11. S. Singh, "Enhancing Observability and Reliability in Wireless Networks with Service Mesh Technologies," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 5, no. 1, 2025, doi: 10.48175/568.
12. G. Sarraf and V. Pal, "Autonomous Threat Detection and Response in Cloud Security: A Comprehensive Survey of AI-Driven Strategies," *Int. J. Emerg. Res. Eng. Technol.*, vol. 6, no. 4, 2025, doi: 10.63282/3050-922X.IJERET-V6I4P114.
13. N. K. Prajapati, "Cloud-based serverless architectures: Trends, challenges and opportunities for modern applications," *World J. Adv. Eng. Technol. Sci.*, vol. 16, no. 1, pp. 427–435, 2025, doi: 10.30574/wjaets.2025.16.1.1225.
14. S. Singh, "Open Radio Access Networks in Multi - Vendor Environments : A Survey of Interoperability Solutions and Best Practices," *Int. J. Innov. Sci. Res. Technol.*, vol. 10, no. 2, 2025.
15. R. Peterkin and D. Ionescu, "Embedded MPLS architecture," *Proc. - 19th IEEE Int. Parallel Distrib. Process. Symp. IPDPS 2005*, vol. 2005, no. January 2005, 2005, doi: 10.1109/IPDPS.2005.195.
16. S. Schmid, M. K. Schou, J. Srba, and J. Vanerio, "R-MPLS: recursive protection for highly dependable MPLS networks," in *Proceedings of the 18th International Conference on emerging Networking EXperiments and Technologies*, 2022, pp. 276–292. doi: 10.1145/3555050.3569140.
17. R. P. Mahajan, "Transfer Learning for MRI image reconstruction: Enhancing model performance with pretrained networks," *Int. J. Sci. Res. Arch.*, vol. 15, no. 1, pp. 298–309, Apr. 2025, doi: 10.30574/ijsra.2025.15.1.0939.
18. H. S. Chandu, "Performance Evaluation of AMBA-3 AHB-Lite Protocol Verification : Techniques and Insights," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 4, no. 2, pp. 201–210, 2024, doi: 10.48175/IJARSCT-19836.
19. W. Zhou *et al.*, "Design and Implementation of Semi-Physical Platform for Label Based Frame Switching in Integrated Satellite Terrestrial Networks," *Appl. Sci.*, 2022, doi: 10.3390/app12136674.
20. S. Tyagi, T. Jindal, S. H. Krishna, S. M. Hassen, S. K. Shukla, and C. Kaur, "Comparative Analysis of Artificial Intelligence and its Powered Technologies Applications in the Finance Sector," in *2022 5th International Conference on Contemporary Computing and Informatics (IC3I)*, 2022, pp. 260–264. doi: 10.1109/IC3I56241.2022.10073077.
21. L. M. Silalahi *et al.*, "Application of MPLS Tunnel Service L2TP-VPN Optimization Concept with Traffic Engineering Method for Looping-Protection Service Analysis," *Int. J. Electron. Telecommun.*, vol. 69, no. 1, pp. 115–120, 2023, doi: 10.24425/ijet.2023.144339.
22. S. Arora, S. R. Thota, and S. Gupta, "Data Mining and Processing in the Age of Big Data and Artificial Intelligence - Issues, Privacy, and Ethical Considerations," in *2024 4th Asian Conference on Innovation in Technology (ASIANCON)*, 2024, pp. 1–6. doi: 10.1109/ASIANCON62057.2024.10838087.
23. S. Arora and S. R. Thota, "Using Artificial Intelligence with Big Data Analytics for Targeted Marketing Campaigns," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 4, no. 3, pp. 593–602, 2024, doi: 10.48175/IJARSCT-18967.
24. R. Hussain and A. Professor, "A Exploration of Multi-Protocol Label Switching (Mpls) Network: a Review," *Artic. J. Crit. Rev.*, no. September, 2020.
25. S. Garg, "Predictive Analytics and Auto Remediation using Artificial Inteligence and Machine learning in Cloud Computing Operations," *Int. J. Innov. Res. Eng. Multidiscip. Phys. Sci.*, vol. 7, no. 2, 2019, doi: 10.5281/zenodo.15362327.
26. Abhishek and P. Khare, "Cloud Security Challenges: Implementing Best Practices for Secure SaaS Application Development," *Int. J. Curr. Eng. Technol.*, vol. 11, no. 06, Nov. 2021, \ doi: 10.14741/ijcet/v.11.6.11.
27. S. Amrale, "Anomaly Identification in Real-Time for Predictive Analytics in IoT Sensor Networks using Deep," *Int. J. Curr. Eng. Technol.*, vol. 14, no. 6, pp. 526–532, 2024, doi: 10.14741/ijcet/v.14.6.15.
28. A. Mushtaq and M. S. Patterh, "QOS parameter comparison of DiffServ-aware MPLS network using IPv4 and IPv6," in *2017 International Conference on Recent Innovations in Signal processing and Embedded Systems (RISE)*, IEEE, Oct. 2017, pp. 113–118. doi: 10.1109/RISE.2017.8378136.
29. S. Murri, S. Chinta, S. Jain, and T. Adimulam, "Advancing Cloud Data Architectures: A Deep Dive into Scalability, Security, and Intelligent Data Management for Next-Generation Applications," *Well*

Test. J., vol. 33, no. S2, 2024.

30. K. S. Hebbar, "Workload-Aware Machine Learning for Microservice Scaling in Kubernetes," *Int. J. Comput. Exp. Sci. Eng.*, vol. 11, no. 4, Dec. 2025, doi: 10.22399/ijcesen.4546.
31. N. Suhaimy, W. Ahmad, N. Radzi, F. Abdullah, MZ Jamaludin, and M. Zakaria, "Analysis of MPLS-TP Network for Different Applications," *Int. J. Eng. Technol.*, vol. 7, no. 4.35, pp. 892–898, Nov. 2018, doi: 10.14419/ijet.v7i4.35.26277.
32. S. R. Thota, S. Arora, and S. Gupta, "Al-Driven Automated Software Documentation Generation for Enhanced Development Productivity," in *2024 International Conference on Data Science and Network Security (ICDSNS)*, 2024, pp. 1–7. doi: 10.1109/ICDSNS62112.2024.10691221.
33. S. K. Chintagunta, "Survey of Containerization , Orchestration , and CI / CD Integration on DevOps in Modern Software Development," *Int. J. Curr. Eng. Technol.*, vol. 13, no. 6, pp. 610–618, 2023.
34. P. Chandrashekar, "Enhancing Software Application Efficiency Through Design- Centric Methodologies : An Empirical Evaluation," vol. 2, no. 1, pp. 187–196, 2022, doi: 10.56472/25832646/JETA-V2I1P122.
35. S. Garg and M. A. E, "Multi-Domain Network Monitoring System for End-to-End Connectivity," *Int. J. Innov. Technol. Explor. Eng.*, vol. 9, no. 7, pp. 1191–1195, May 2020, doi: 10.35940/ijitee.G5865.059720.
36. S. Thangavel, K. C. Sunkara, and S. Srinivasan, "Software-Defined Networking (SDN) in Cloud Data Centers: Optimizing Traffic Management for Hyper-Scale Infrastructure," *Int. J. Emerg. Trends Comput. Sci. Inf. Technol.*, vol. 3, no. 1, pp. 29–42, 2022, doi: 10.63282/3050-9246.IJETCSIT-V3I3P104.
37. S. Pandya, "Innovative blockchain solutions for enhanced security and verifiability of academic credentials," *Int. J. Sci. Res. Arch.*, vol. 6, no. 1, pp. 347–357, Jun. 2022, doi: 10.30574/ijsra.2022.6.1.0225.
38. H. P. Cyril, "Event-Driven Provisioning Architectures For Modern Telecom Networks: Overcoming Legacy Limitations And Enabling Autonomous 6g Operations," *Int. J. Adv. Res. Comput. Sci.*, vol. 16, no. 6, pp. 75–82, Dec. 2025, doi: 10.26483/ijarcs.v16i6.7389.
39. N. Raveendran, "Comparative Evaluation of Persistent vs. In-Memory Stream Exchange in Big Data Systems: A Technical Review," *J. Comput. Sci. Technol. Stud.*, vol. 7, no. 7, pp. 172–182, Jul. 2025, doi: 10.32996/jcsts.2025.7.7.15.
40. R. Patel and P. B. Patel, "The Role of Simulation & Engineering Software in Optimizing Mechanical System Performance," *TIJER – Int. Res. J.*, vol. 11, no. 6, pp. 991–996, 2024, doi: 10.56975/tijer.v11i6.158468.
41. V. Prajapati, "Role of Identity and Access Management in Zero Trust Architecture for Cloud Security : Challenges and Solutions," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 5, no. 3, pp. 6–18, 2025, doi: 10.48175/IJARSCT-23902.
42. S. K. Davuluri, V. Challagulla, V. Mudapaka, and U. Konka, "AI-Driven DevOps in Telecommunications: Bridging Predictive Analytics with Continuous Delivery for Network Agility," in *2025 IEEE International Conference and Expo on Real Time Communications at IIT (RTC)*, Oct. 2025, pp. 1–4. doi: 10.1109/RTC66985.2025.11211551.
43. S. Kumara, "Zero Trust Identity Fabric for Multi-Layer Telecom Networks: Implications for Secure and Scalable Digital Infrastructure," *Int. J. Curr. Eng. Technol.*, vol. 15, no. 6, 2025.
44. M. A. Ridwan, N. A. M. Radzi, W. S. H. M. Wan Ahmad, F. Abdullah, M. Z. Jamaludin, and M. N. Zakaria, "Recent trends in MPLS networks: technologies, applications and challenges," *IET Commun.*, vol. 14, no. 2, pp. 177–185, Jan. 2020, doi: 10.1049/iet-com.2018.6129.
45. V. Shah, "An Analysis of Dynamic DDoS Entry Point Localization in Software-Defined WANs," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 4, no. 6, pp. 442–455, Nov. 2024, doi: 10.48175/IJARSCT-22565.
46. M. Melad, M. Musbah, and K. Almiqasbi, "Evaluating Segment Routing Technology for MPLS-based Network," *E3S Web Conf.*, vol. 469, 2023, doi: 10.1051/e3sconf/202346900075.
47. D. Patel, "Zero Trust and DevSecOps in Cloud-Native Environments with Security Frameworks and Best Practices," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 3, no. 3, pp. 454–464, Jan. 2023, doi: 10.48175/IJARSCT-11900D.
48. D. Wu and L. Cui, "A comprehensive survey on Segment Routing Traffic Engineering," *Digit. Commun. Networks*, vol. 9, no. 4, pp. 990–1008, 2023, doi: 10.1016/j.dcan.2022.02.006.
49. V. Prajapati, "Cloud-Based Database Management : Architecture , Security , challenges and solutions," *J. Glob. Res. Electron. Commun.*, vol. 1, no. 1, 2025, doi: 10.5281/zenodo.14934833.
50. [50] M. Alkasassbeh, G. Al-naymat, and M. Alauthman, "Optimizing Traffic Engineering in," no. November, pp. 1–27, 2018, doi: 10.20944/preprints201811.0486.v1.
51. V. Prajapati, "Blockchain-Based Decentralized Identity Systems: A Survey of Security, Privacy, and Interoperability," *Int. J. Innov. Sci. Res. Technol.*, vol.

10, no. 3, 2025.
52. P. Amaral, E. Silva, L. Bernardo, and P. Pinto, "Inter-domain traffic engineering using an AS-level multipath routing architecture," *IEEE Int. Conf. Commun.*, no. June, 2011, doi: 10.1109/icc.2011.5962887.
53. D. Patel, "The Role of Amazon Web Services in Modern Cloud Architecture: Key Strategies for Scalable Deployment and Integration," *Asian J. Comput. Sci. Eng.*, vol. 9, no. 4, pp. 1–9, 2024.
54. Y. Muni, "Understanding The Evolution Of Internet Protocols: An In-Depth Review Of Ipv4 And Ipv6: A Comparative Review Of Transition Challenges And Solutions," *Int. J. Adv. Res. Comput. Sci.*, vol. 16, no. 4, pp. 109–117, Aug. 2025, doi: 10.26483/ijarcs.v16i4.7307.
55. R. Patel, "Optimizing Communication Protocols in Industrial IoT Edge Networks: A Review of State-of-the-Art Techniques," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 4, no. 19, pp. 503–514, May 2023, doi: 10.48175/IJARSCT-11979B.
56. G. Bernardez *et al.*, "Magnneto: A Graph Neural Network-Based Multi-Agent System for Traffic Engineering," *IEEE Trans. Cogn. Commun. Netw.*, vol. 9, no. 2, pp. 494–506, 2023, doi: 10.1109/TCCN.2023.3235719.
57. S. Chatterjee, "Integrating Identity and Access Management for Critical Infrastructure: Ensuring Compliance and Security in Utility Systems," *Int. J. Innov. Res. Creat. Technol.*, vol. 8, no. 2, pp. 1–8, 2022.
58. M. R. Nedhunuri, H. V. Bonala, H. K. Duvvuru, S. D. Bharatula, and S. G, "Implementing Traffic Engineering in MPLS Networks Using Resource Reservation Protocol," in *2024 International Conference on Smart Electronics and Communication Systems (ISENSE)*, 2024, pp. 1–6. doi: 10.1109/ISENSE63713.2024.10872144.
59. S. Jiang and N. Sakamoto, "Segment Routing Traffic Engineering by Pruned Landmark Labeling," in *2023 IEEE/ACIS 8th International Conference on Big Data, Cloud Computing, and Data Science (BCD)*, 2023, pp. 237–244. doi: 10.1109/BCD57833.2023.10466314.
60. M. Alja' afreh, M. Obaidat, and S. Alouneh, "Incorporating MPLS for Better SoC Utilization and Traffic Engineering," in *2022 Seventh International Conference on Fog and Mobile Edge Computing (FMEC)*, IEEE, Dec. 2022, pp. 1–7. doi: 10.1109/FMEC57183.2022.10062535.
61. Monika, S. Singh, and A. Wason, "Performance Evaluation of Bandwidth Allocating Algorithms in Generalized Multi Protocol Label Switched Optical Networks to Enhance Quality of Service," *IEEE Access*, vol. 10, pp. 40731–40742, 2022, doi: 10.1109/ACCESS.2022.3166912.
62. J. A. Singh, M. R. S. Kumar, and K. S. Shushrutha, "Implementation of Segment Routing-Traffic Engineering over MPLS," in *2021 12th International Conference on Computing Communication and Networking Technologies (ICCCNT)*, IEEE, Jul. 2021, pp. 1–5. doi: 10.1109/ICCCNT51525.2021.9579691.
63. P. S. Aurel, P. Gabriel, C. Denisa, A. Nicoleta, and P. Dan Constantin, "Analysis of file transfer traffic using MPLS technology," in *2022 26th International Conference on System Theory, Control and Computing (ICSTCC)*, 2022, pp. 52–57. doi: 10.1109/ICSTCC55426.2022.9931894.