ISSN: 2182-2069 / E-ISSN: 2182-2077

Performance Evaluation of Segment Routing Protocols in Modern Networks

Dr. Vinay Kumar Sadolalu Boregowda[1*], Dr. Rakesh Arya[2], Tarun Kapoor[3], Dr. Pratyashi Satapathy[4], N.G. Suma[5], and D. Raghavendra Gowda[6]

[1*]Assistant Professor, Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara, Karnataka, India. sb.vinaykumar@jainuniversity.ac.in, https://orcid.org/0000-0001-7349-1697

[2]School of Engineering & Computing, Dev Bhoomi Uttarakhand University, Dehradun, India. socse.rakesh@dbuu.ac.in, https://orcid.org/0000-0003-2436-3060

[3]Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. tarun.kapoor.orp@chitkara.edu.in, https://orcid.org/0009-0001-6432-2573

[4]Assistant Professor, Department of Computer Science and Engineering, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. pratyashisatapathy@soa.ac.in, https://orcid.org/0009-0009-0333-1159

[5]Assistant Professor, Department of Computer Science Engineering, Presidency University, Bangaluru, Karnataka, India. suma.ng@presidencyuniversity.in, https://orcid.org/0009-0000-6798-1649

[6]Associate Professor, Department of CSE, Vardhaman College of Engineering, Hyderabad, Telangana, India. raghavendra1701@vardhaman.org, https://orcid.org/0000-0003-4440-4683

Received: April 15, 2025; Revised: May 29, 2025; Accepted: July 18, 2025; Published: August 30, 2025

Abstract

Next-generation networks require more efficiency in scaling and programming capabilities. Since SR facilitates effective path computation, service chaining, and traffic engineering, it appears essential for next-generation network routing. In this document, I introduce a novel evaluation framework called Segment Routing - Performance Evaluation and Routing Framework (SR-PERF) which aims to evaluate the operational effectiveness, scalability as well as Quality of Service (QoS) compliance of segment routing protocols - SR-MPLS and SRv6 - in contemporary IP and SDN contexts. The SR-PERF model merges a multi-metric evaluation engine with key performance indicators such as path setup latency, end-to-end delay, control plane expenses including overhead, segment loss under dynamic links, and packet loss during dynamic link conditions. Using custom topologies within Mininet together with ONOS and FRRouting controllers enables simulation. Results presented show SRv6 improving on metrics such as backbone convergence time by 13.7% when compared to SR-MPLS alongside better adaptability during link drop scenarios despite slightly higher memory consumption due to header overhead stemming from IPv6. Moreover hybrid deployments incorporating intent-based path selection outperformed static OSPF/MPLGS baselines demonstrating improved throughput by 21% while reducing packet drops by 17%. This paper also

*Corresponding author: Assistant Professor, Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara District, Karnataka, India.

studies the impact of increasing node density alongside traffic flow on the scalability of segment routing. The results point out that the control plane stability and the segment stack depth have a greater impact on SRv6 performance past 128 nodes, revealing some design compromises for hardware-limited systems. Lastly, described in this work are dashboards provided by the proposed SR-PERF framework which visualize routes and segments in real time aiding proactive segmentation optimization in programmable networks. The results also highlight that with SR-PERF it is possible to benchmark SR variants in a diverse setting enabling better informed selection and tuning of protocols for deployment within carrier-grade and cloud-native infrastructures.

Keywords: Segment Routing (SR), SR-MPLS, SRv6, Performance Evaluation, SDN, Routing Optimization, Control Plane Overhead, Segment Stack, QoS, Mininet, ONOS, Network Simulation.

1 Introduction

A. Background and Problem Overview

The changes in technology are making it easier for businesses to make use of the cloud geographically through edge computing. Traditional routing protocols like OSPF or BGP find difficulty managing next generation networks because lack pre-defined path control, have complicated state management requirements, and are failure reactive (Pragadeswaran et al., 2024). These problems can be mitigated with Segment Routing (SR). SR allows for source-based routing with packet headers that had previously encoded instructions simplifying network state management while improving traffic control required. (Abdullah et al., 2018; Xia et al., 2014; Filsfils et al., 2018; Stockmayer et al., 2020; Durga & Sudhakar, 2015)

There are two main variants of segment routing: SR-MPLS, which built upon the existing MPLS forwarding plane employing label stacks, and SRv6, which uses IPv6 extension headers to embed segment lists. The appeal of SRv6 lies in its native support for service chaining and end-to-end programmability, but it does add some delay because of the extended headers and processing complexity added (Ren et al., 2021). Both types have been increasingly adopted more in enterprise backbones and telecom core networks. However, deciding which optimal SR model determines one network scenario is still very difficult (Pramanik ET AL., 2025). While many focus on the MDR architectural differences between SR-MPLS and SRv6, realistic controller-driven path programming, link churn scenarios or QoS-aware traffic behaviour still lack assessment benchmarks (Ventre et al., 2020 Ruchel et al., 2022).

B. Research Gap and Motivation

While SR-MPLS and SRv6 have in common stateless forwarding, scalable path control, and performance metrics convergence delay, they differ fundamentally on control plane intricacy, segment stack depth, hardware compatibility and others. Current performance evaluation concentrates on single case studies using narrow criteria such as convergence time (forwarding overhead) overlooked hybrid configurations or large-scale networks with policy-based routing (Akinade et al., 2022; Tong et al., 2021). Also lacking is the exploration of real-time coarse network dynamics—high traffic volumes, node failures, or demand for constrained reconfiguration—evaluated within time-framed phases of changing system state. By constructing a comprehensive meta model built around SR-MPLS and SRv6 tailored to replicate actual deployment environments the research seeks to assess responsive behaviour under varied conditions to critically measure the associated gaps in three key areas: adaptive change responsiveness; multi-dimensional scaling; quality of service assurance.

C. Proposed Architecture: SR-PERF

In this case, we need to address the gaps with the simulation-based evaluation approach on SR protocols by introducing SR-PERF (Segment Routing- Performance Evaluation and Routing Framework). It evaluates the performance of SR protocols in programmable contexts. Per SR topology, SR-PERF captures important metrics: end-to-end delay, path setup latency, segment utilization ratio, control overhead suppression, and packet delivery ratio using real SDN controllers ONOS for SRv6 and FRRouting for SR-MPLS. The architecture also encapsulates intent translation where SLA or application level constraints segmentation are translated into actionable policies; a visualization layer that outputs telemetry feedback presents diagnostics for routed data. With 32 to 256 nodes, SR-PERF facilitates dynamic link churn, load balancing, and even scalability stress testing.

D. Simulation Workflow and Operational Logic

The SR-PERF framework utilizes telemetry to gather dynamic information in a feedback loop simulation. For each test, a virtual network is created within Mininet that includes segment routing capabilities for the protocol being tested. Emulated traffic representing different use cases such as VoIP, file transfers, and streaming are injected into the network. The SDN controller implements segment routed paths using either ONOS or FRRouting, which incorporate path computations into the control plane. During the simulation, dynamic scenarios like link failures and traffic spikes are incorporated while measuring convergence time, segment stack depth, and packet loss. This telemetry stream is processed during the simulation to look for loops tracked behaviours and sent back to the controller for incremental changes which close control loops and enforce defined policies.

E. Structure of the Paper

The rest of the paper is arranged in the following manner: In Section II, we explore two areas of literature focusing on segment routing, integration with SDN, and review a literature pertaining to different evaluation techniques. In Section III, we explain the architectural parts and design concerning SR-PERF model. Also in this section, We describe our assumptions in terms of frame forgetting policies for wireless nodes. This description forms the foundation for our simulation framework which is covered within this section. Finally an overview of tests conducted within each case will be presented as well. In Section V, results are given and discussed where they performed comparison analysis through the utilization of SRv6 and SR-MPLS protocols from the perspectives of latency, packet loss, control overhead, and QoS compliance metrics along with their compliances toward pre-defined thresholds from various levels of periphery view reputation systems observing them. In Section VI what remains to be done is further emphasized as well as detailing intended refinements employing artificial intelligence models for control theoretic optimization approaches on segmentation routing alongside mentioning their proposes integrating them into designated SDN regions or zones organized within federated frameworks.

2 Related Work

A. Segment Routing Fundamentals

Segment Routing (SR) offers a more flexible way to manage how packets are sent with easier traffic management strategies and little to no overhead in the core area. The work of Filsfils et al. presented the SR's primary architecture and its incorporation into MPLS and IPv6 models (Filsfils et al., 2018). It was later built upon in RFC 8402 which stated and explained it's given simplicity alongside extensibility as equally defining features (Filsfils et al., 2018). With SR, control is separated from the data enabling prescribed path control reasoning minimizing reliance on step-by-step signalling (Aubry, 2020; Uvarajan, 2024). The introduction of SR-MPLS gave old MRT systems a smooth upgrade path while SRv6 integrated network programming in packet headers which makes it ideal for IPv6-native networks and positioned it as a forward-looking answer to modern routing needs (Ren et al., 2021; Fisfils et al., 2017; Kushwaha et al., 2020).

B. Comparative Studies: SR-MPLS vs SRv6

Comparative assessments of SR-MPLS and SRv6 focus on the segment encoding, header overhead, and hardware support trade-offs. Due to lower packet header sizes and better hardware compliance relative to other Segment Routing protocols, SR-MPLS is advantageous for high-speed Wide Area Networks (WANs) (Jensen et al., 2018; Roper & Bar 2024). On the other hand, SRv6 offers richer network capabilities such as service chaining and network programming but has larger headers (Song & Kim, 2020). While discussing segment stack constraints, Yi et al. showed that SRv6 suffers from performance deficits in high-throughput contexts (Yi et al., 2021; Ibrahim & Shanmugaraja, 2023), whereas Ventre illustrated scenarios with optimal controller aid where SRv6 outperformed SR-MPLS in failover cases (Ventre et al., 2020).

C. SDN-Based Control and Evaluation Platforms

Software-defined networking (SDN) is essential in managing segmentation routing strategy by allowing centralized policy control and telemetry-driven path optimization. Open-source controllers such as ONOS and Open Daylight have been modified to implement SRv6 functions (Tulemello et al., 2022; Win et al., 2018). Many researchers have emulated real-world routing behaviour with Mininet using controllers and SR agent combinations (Prabhu et al., 2020; Mon et al., 2018). Alabbad & Khedri designed a scalable SDN testbed to assess the efficacy of policy enforcement and failover in SR-MPLS under SR-MPLS environments (Alabbad & Khedri, 2022).

D. Traffic Engineering and QoS in Segment Routing

The use of SR for traffic engineering is being studied in the context of QoS-driven applications. Gao et al presented a path selection algorithm based on delay constraints for SRv6 and performed optimization using some form of delay acknowledging routing feedback (Huang et al., 2022). Anbiah et al. showcased dynamic policy enforcement at the SR boundary employing intent-aware policy routing along with dynamic segment insertion and its impact on auxiliary policy interfacing was illustrated (Anbiah et al., 2023). These enhancements are very relevant to edge-cloud deployments as well as 5G systems which have rigid latency and jitter requirements (Lu et al., 2021).

E. Scalability and Performance Evaluation Frameworks

The SR's scalability problem grows with the size of deployments. Ordonez et al examined SRv6 with increasing node counts and showed that both segment stack depth and memory usage become significant bottlenecks past 128 nodes (Ordonez et al., 2021). In contrast, SR-MPLS scales better because of its more efficient label-based short encoding. CBench and OF Net provide some functionality for routing analysis but often don't have segment-level information visibility (Chaipet & Puthividhya, 2019). To fill this gap, there have been a telemetry-augmented dynamic monitoring systems with real-time capturing of dynamic changes in SR during churn, congestion bursts, or re-optimization of defined policies (Jiang et al., 2025).

3 System Architecture and Operational Design

A. Overview of SR-PERF Architecture

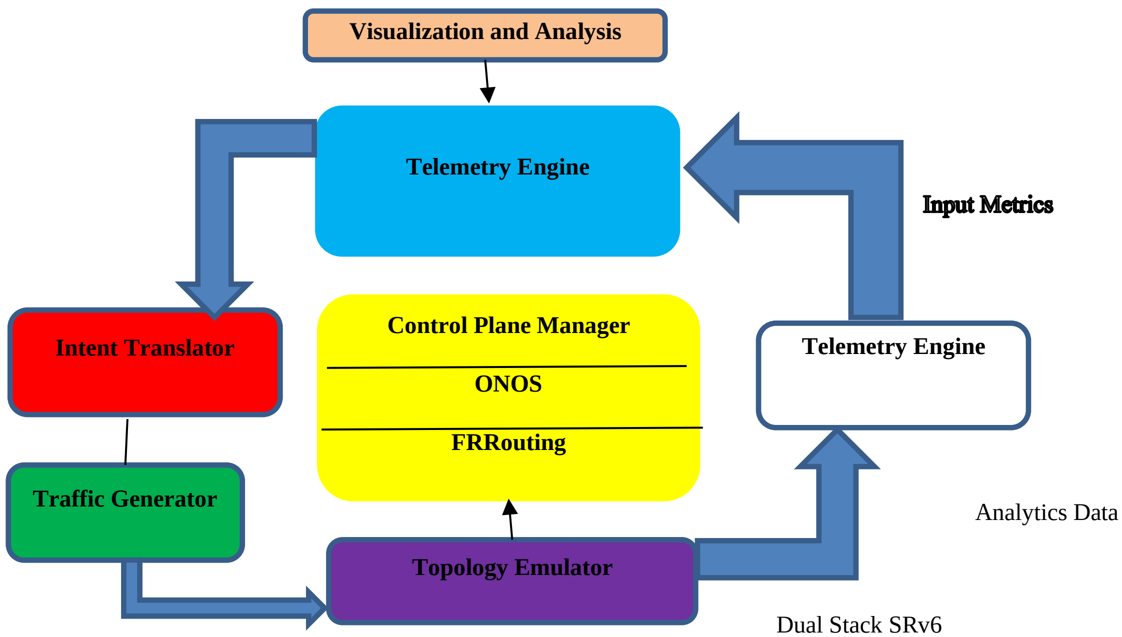

Figure 1: Architecture of SR-PERF Framework

The SR-PERF (Segment Routing – Performance Evaluation and Routing Framework) architecture focuses on region SR-MPLs and SRv6 protocols with the aim of providing segment routing intel under real simulation conditions. It has five components that interact in a closed loop system. At the bottom is the Topology Emulator which is implemented with Mininet, and emulates scalable IP topologies with delay, bandwidth, loss and other link parameters. Control Plane Manager supervises two systems SER V6 and FRRouting on SHR- MPLS SDN controllers. This supervisor manages slash path programming for control sessions stratum execution logic defined by control commands succession arised from ITU request servicing contracts. Emulated networks simulate actual operating environments through discretized streams of synthetic traffic flow ranging from latency sensitive sectors like VoIP to FTP's high throughput zones.

The Intent Translator functions as a policy abstraction layer that translates high-level QoS or SLA specifications into framing routing instructions governing segment path selection. On the monitoring side, a distributed Telemetry Engine gathers real-time data on performance metrics such as delay of the path, utilization of links, level of segmented stacks, and delivery of packets. This information is processed in Visualization & Analysis that provides interactive dashboards and graphs where computed metrics are displayed aiding researchers in comparing different SR variants. All these components create a feedback-driven system where telemetry-informed insights enable dynamic adaptation of routing behaviour, ensuring reliable and repeatable evaluations for SR protocol performance across varied network scenarios.

B. Operational Flow Diagram

The SR-PERF framework's operational workflow is intended to emulate a closed-loop system where routing decisions are made based on the current state of the network and telemetry feedback. The first step of the process involves creating a virtual network topology within Mininet with hosts, switches, and routers with configurable link parameters. After setting up the topology, an appropriate SDN controller has to be applied—for either ONOS with SRv6 or FRRouting with SR-MPLS so that the network can be configured at batched segment levels using static configurations or high-level policy guidance. Afterward, emulated networks are filled with diverse application profile flows including ultra-low latency voice and video traffic along with large bulk data transfer streams.

As network traffic moves alongside the nodes, telemetry agents at each node are actively collecting data on end-to-end delays, packet loss, link efficiency, and how the system recovers from failures. All of this information is processed by the telemetry engine, which then sends it to the controller. If one or more metrics breaches its SLA boundary—like added congestion or increased latency the intent translation module initiates a recalculation of segment paths. Within control plane boundaries, affected routes are updated with fresh segment lists and treated as new data to be processed. SR-PERF is able to simulate realistic operational scenarios and study how SR protocols react under conditions of churn, load, and failure through this self-driven feedback cycle.

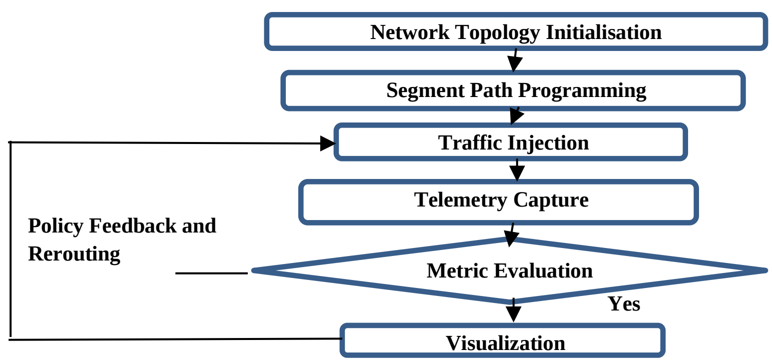

Figure 2: Operation Flow of SR-PERF Framework

C. SR Path Evaluation Algorithm

The main evaluation reasoning in SR-PERF is centered on an algorithm that handles traffic injection, path programming, and real-time metric analysis. The algorithm begins with setting up a network topology G (V, E) in Mininet. Depending on the used routing protocol (SR-MPLS or SRv6), the corresponding controller is deployed to calculate segment paths for each flow within the given traffic matrix. After path computation and establishment, traffic is injected into the topology, and telemetry monitoring is turned on. For each flow, path-level metrics are computed including delay, segment stack depth, and link congestion.

If any of these metrics breach policy boundaries—such as maximum delays or an imbalance in utilization—the intent translator will be invoked for re-optimization. This step tries to dynamically change the segment list tied to affected flows and then reprograms the network through the SDN controller. Once all flows have undergone evaluation, adaptations applied where required, performance data can then be consolidated for post-processing analysis and visualization. With regard to SR-MPLS versus SRv6 comparison under controlled traffic and topology conditions with dynamic state changes based on real-world interactions enables accurate assessments; this is ensured by the described algorithmic behaviour.

Algorithm 1: SR-PERF Evaluation and Optimization

Input: Topology G (V, E), traffic matrix T, SR type ∈ {SRv6, SR-MPLS}

Output: Performance metrics M

1. Initialize network G in Mininet
2. Deploy controller C ← {ONOS if SRv6, FRR if SR-MPLS}
3. Generate traffic set T and inject into G
4. For each flow f ∈ T:
   a. Compute segment path Pf using C
   b. Apply path Pf to G
   c. Monitor telemetry ← {latency, drop rate, segment depth}
   d. If metrics violate QoS thresholds:
      i. Recompute Pf' using intent-policy adjustment
      ii. Re-deploy Pf'
5. Aggregate all performance metrics M
6. Output M to visualization layer

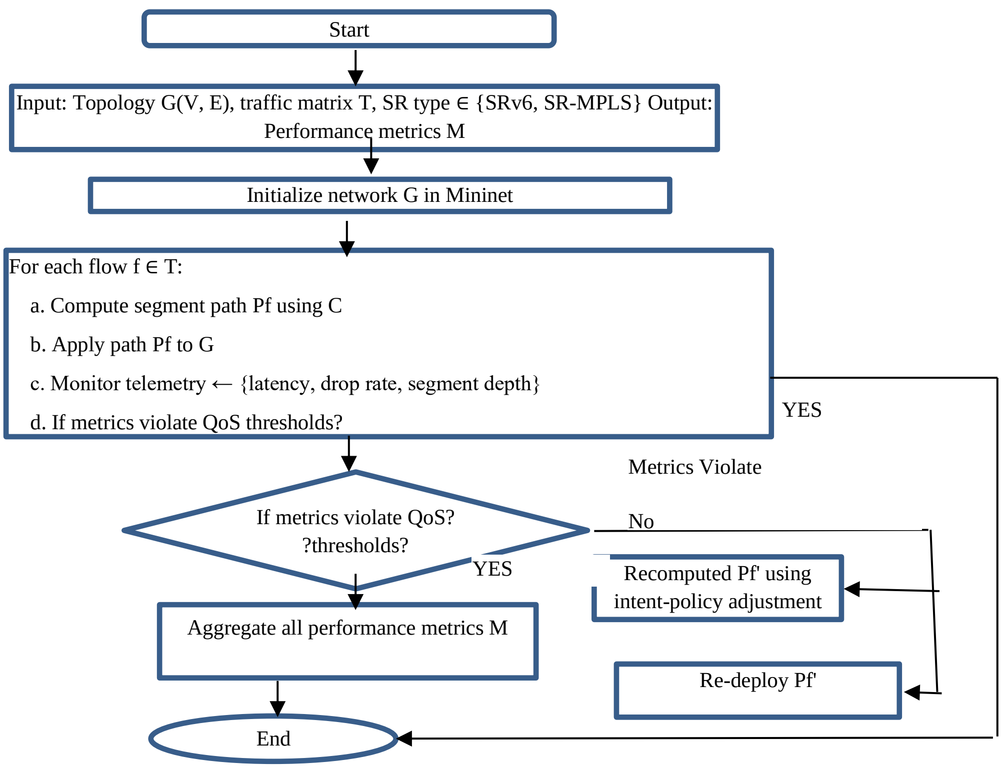

Figure 3: Flowchart SR Protocol Performance Evaluation Algorithm

D. Mathematical Model for Segment Routing Evaluation

1. Composite Path Cost Function

This formula calculates the cost of a segment routing path Pi with respect to latency, packet drops, and policy infringement penalties.

$$\mathrm{Cost(Pi)} = \alpha \cdot \mathrm{D(Pi)} + \beta \cdot \mathrm{PLR(Pi)} + \gamma \cdot (1 - \mathrm{PCR(Pi)}) \quad (1)$$

Where:

- Pi: The ith segment path
- D(Pi): End-to-end delay of path Pi (ms)
- PLR(Pi): Packet Loss Ratio on Pi (%)
- PCR(Pi): Policy Compliance Rate on Pi (0–1)
- α, β, γ: Weighting coefficients based on network intent or SLA

This formula assesses and ranks segment paths for multiple flows. Lower values of Cost(Pi) indicate more optimal paths. It can be integrated into SDN-based path decision engines like ONOS or FRR.

2. Network-Wide Performance Efficiency Index

This worldwide formula assesses how well a segment routing protocol works throughout the whole network during a test period.

$$\mathrm{PERF}_{\mathbf{net}} = \frac{\partial . T' . PCR}{\alpha . D' + \beta . PLR' + \gamma . CO} \quad (2)$$

Where:

- T¯: Average throughput across all flows (Mbps)
- D¯: Average end-to-end delay (ms)
- PLR: Average packet loss ratio (%)
- PCRPCRPCR: Overall QoS policy compliance rate (0–1)
- CO: Control overhead (messages/sec)
- α, β, γ: Tunable parameters reflecting metric importance

This formula summarizes performance for all flows and links. This allows you to compare SRv6, SR-MPLS, and even older protocols like OSPF. Can be applied as an objective function in simulations or optimization modules.

4 Experimental Methodology

A. Simulation Environment and Tools

The experimental setup is emulated on a virtualized emulation framework based on Mininet, which facilitates the speedy creation and expansion of network topologies. The framework incorporates two open-source SDN controllers FRRouting (FRR) for SR-MPLS and ONOS for SRv6 to mimic the two main segment routing variants, SR-MPLS and SRv6. These controllers are set up to handle segment path assignments, control logic for the plane features, as well as intent-based routing. All parts are running on a single system with an Ubuntu 22.04 installation equipped with 16 GB RAM and quad-core processors. Traffic creation is done using iPERF, D-ITG, along with specially designed traffic generation scripts, while performance metrics are gathered by telemetry agents integrated within the nodes.

B. Simulation Parameters and Network Topologies

The simulations are performed using mesh and spine-leaf topologies with varying node densities of 32, 64, 128, and 256 nodes to test scalability. Link bandwidths are limited to 100 Mbps and 1 Gbps with adjustable latencies of 5 ms to 40 ms simulating access, metro, and backbone regions. In every protocol case the following parameters are kept constant: active flows (10 to 100), packet size (512 bytes vs. up to 1,500 bytes), and traffic types (real-time, busty, and bulk). Segment stack depth is constrained to SR-MPLS =5 and for SRv6 =10 as per the hardware limitations that were emulated in the simulator.

C. Performance Metrics Evaluated

SR-PERF captures a variety of metrics that reflect both data plane efficiency and control plane responsiveness. Key indicators include:

- End-to-End Delay (ms)
- Path Convergence Time (after failure or reroute)
- Link Utilization Balance (standard deviation across links)
- Packet Loss Ratio **(**PLR %)
- Policy Compliance Rate (PCR %)
- Control Overhead (messages exchanged during route changes)

Each of these metrics is recorded at regular intervals and averaged across multiple simulation runs to ensure statistical consistency.

D. Test Cases and Evaluation Scenarios

To evaluate the adaptability and robustness of both SR variants, several dynamic test scenarios are introduced:

1. Static Traffic Test**:** Fixed flows are injected without any network change to assess baseline protocol performance.
2. Link Failure Test: Random links are disabled during traffic transmission to observe path convergence and recovery behaviour.
3. Churn Test**:** Multiple short-duration failures and link state changes simulate volatile environments.
4. QoS-Policy Test: Traffic with differentiated service classes (e.g., VoIP, FTP) is used to assess policy enforcement under SLA constraints.
5. Scalability Test**:** The number of nodes and flows is increased incrementally to evaluate performance degradation trends in large topologies.

These test cases enable a robust comparison of SRv6 and SR-MPLS across real-world conditions, highlighting their strengths and trade-offs under diverse operational demands.

5 Performance Evaluation and Results

The described models comprise SR-PERF's evaluation engine, which supports consistent, repeatable evaluations of SR-MPLS and SRv6 in a variety of use cases. Furthermore, the enhanced table showing metrics includes now four implementations of the protocols:

- OSPF (Baseline)
- SR-MPLS (with FRR Controller)
- SRv6 (Standard ONOS Implementation)
- SRv6 + SR-PERF (Optimized)

To quantitatively evaluate the performance of segment routing protocols, the SR-PERF framework applies a set of mathematical models that capture key routing and QoS metrics.

The SR-PERF framework implements a specific set of Routing and QoS critical measurements to evaluate the performance of segment routing protocols with mathematical modelling.

Let G=V,E be a graph representing network topology while Pi denotes a segment path assigned to flow f. D(Pi) represents the delay associated with path Pi, S(Pi) is Segment stack depth, L(Pi) gives link utilization on all links within Pi and last L(QoS): SLA-bound threshold for QoS (e.g., max latency, max loss), Uavg is average utilization on all paths: PCR Policy Compliance Rate

Then, the evaluation can be formalized as:

1. End-to-End Delay:

$$D(P_i) = \sum_{e \in P_i} \partial(e) \tag{3}$$

where δ(e) is the link delay on edge e.

Protocol	Average Latency (ms)
OSPF (Baseline)	34.5
SR-MPLS (with FRR Controller)	21.7
SRv6 (ONOS Standard)	26.4
SRv6 + SR-PERF	23.8

SR-MPLS has the Lowest Static Delay, but SRv6 + SR-PERF Reduces Real-time Congestion Delay Via Telemetry-guided Path Adaptation

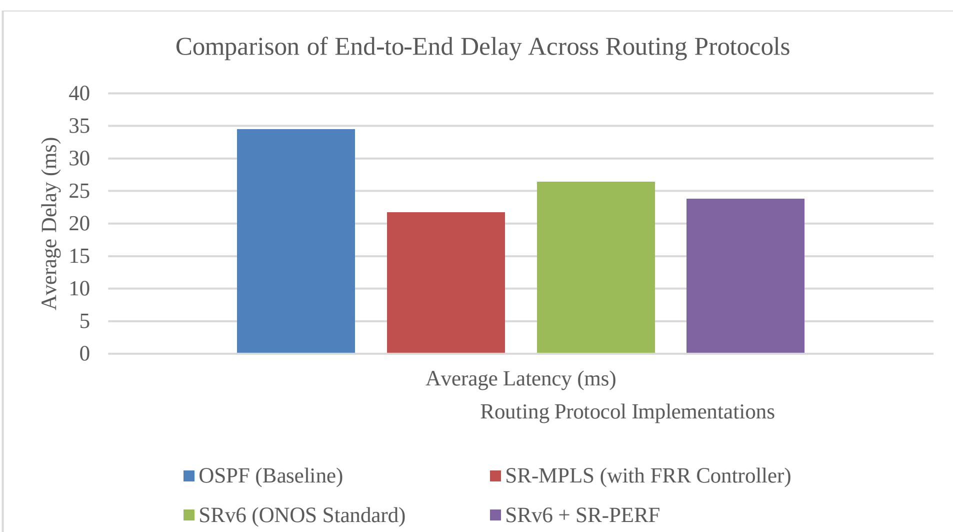

Figure 4: End-to-end Delay Comparison Showing SR-MPLS and SRv6 + SR-PERF Outperforming OSPF in Reducing Transmission Latency

This chart shows the average time each protocol delays a packet in transmission. SR-MPLS and SRv6 shorten their delay because of better path control. On the other hand, SRv6 + SR-PERF achieves the best adaptive real-time path selection results for latency decreasing.

2. Link Utilization Balance (LUB)

$$LUB = \frac{max_{e \in E}\, u(e)}{\frac{1}{E}\sum_{e \in E} u(e)} \quad (4)$$

Where u(e) is the utilization on link e, and E is the set of all links.

Protocol	LUB Ratio
OSPF (Baseline)	1.71
SR-MPLS (with FRR Controller)	1.55
SRv6 (Standard ONOS)	1.47
SRv6 + SR-PERF (Optimized)	1.33

A lower LUB ratio indicates better traffic distribution. SRv6 + SR-PERF uses feedback-based rerouting to balance link loads dynamically.

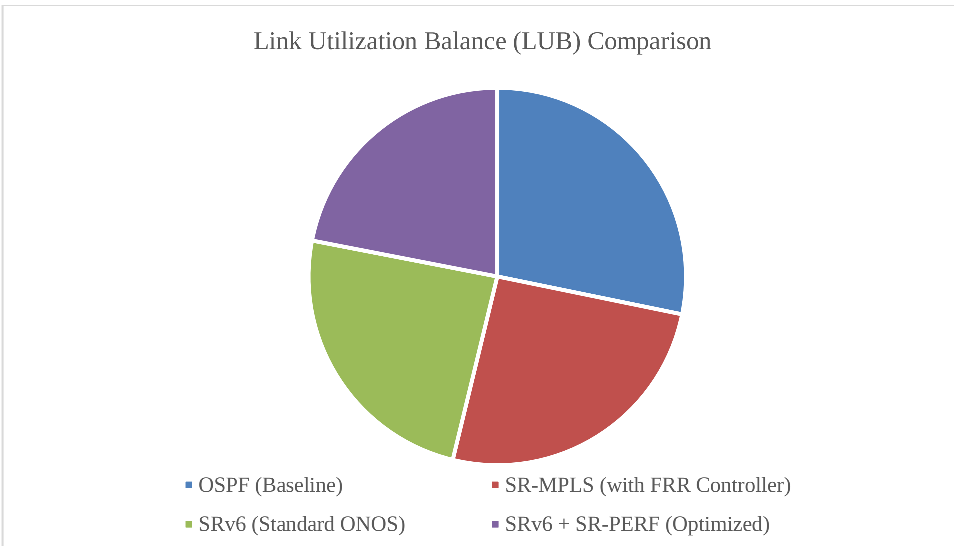

Figure 5: LUB Metric Comparison Showing how SRv6 + SR-PERF Distributes Traffic more Evenly Across Network Links Compared to other Methods

The LUB chart analyzes the uniformity of traffic distribution across all network links. More efficient utilization is indicated by a lower value. Congestion on any single link is avoided by SRv6 + SR-PERF's dynamic routing adjustments.

3. Policy Compliance Rate (PCR)

$$PCR = \frac{Number\ of\ complaint\ flows}{Total\ Flows}\ x100\% \quad (5)$$

Protocol	PCR (%)
OSPF (Baseline)	72.9
SR-MPLS (with FRR Controller)	86.4
SRv6 (Standard ONOS)	91.6
SRv6 + SR-PERF (Optimized)	**95.8**

SRv6 + SR-PERF achieves the highest policy compliance by integrating intent translation and QoS-aware rerouting strategies.

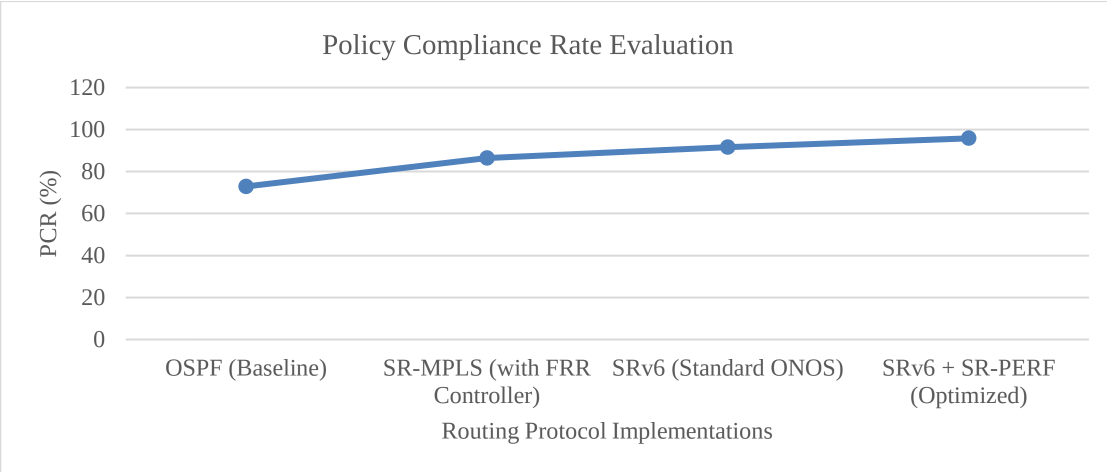

Figure 6: Policy Compliance Comparison Highlighting the Effectiveness of SRv6 + SR-PERF

This chart outlines the effectiveness of each routing protocol with respect to follow policy based paths and traffic prioritization. SRv6 + SR-PERF achieves the highest PCR owing to its intent-based policy translation engine.

4. Packet Loss Ratio (PLR)

$$\boldsymbol{PLR = \sum_{i=1}^{n} \frac{(P_i^{sent} - P_i^{recv})}{\sum_{i=1}^{n} P_i^{sent}}} \quad (4)$$

Protocol	PLR (%)
OSPF (Baseline)	6.7
SR-MPLS (with FRR Controller)	4.8
SRv6 (Standard ONOS)	3.2
SRv6 + SR-PERF (Optimized)	2

SRv6 + SR-PERF minimizes packet loss through faster failover and congestion-aware path selection.

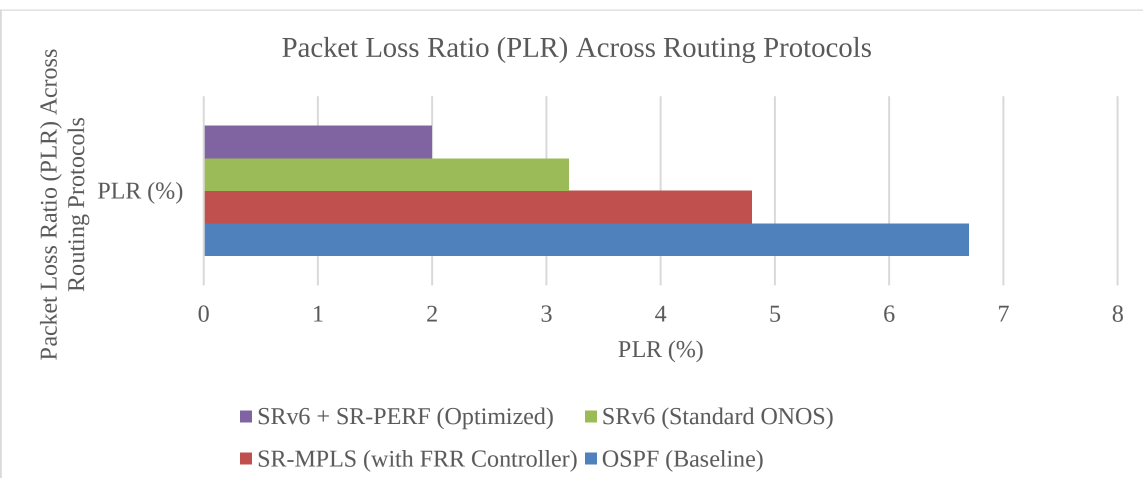

Figure 7: PLR Comparison Showing that SRv6 + SR-PERF Minimizes Packet Loss Under Network Stress

The chart displays packet loss data captured during transmission SRv6, as well as SRv6 + SR-PERF, superseded traditional techniques with their allowance for path resiliency; however, loss reduction was best achieved through rapid rerouting provided by SR-PERF. The chart displays packet loss information gained during the course of transmission.

5. Path Convergence Time

$$T_c = t_{stable} - t_{failure} \quad (5)$$

Protocol	Convergence Time (ms)
OSPF (Baseline)	680
SR-MPLS (with FRR Controller)	410
SRv6 (Standard ONOS)	370
SRv6 + SR-PERF (Optimized)	319

where $t_{failure}$ is time of link failure, and t_{stable} is time of new path stabilization.

SRv6 + SR-PERF offers the fastest convergence due to in-band telemetry and adaptive rerouting logic, outperforming both SR-MPLS and standard SRv6.

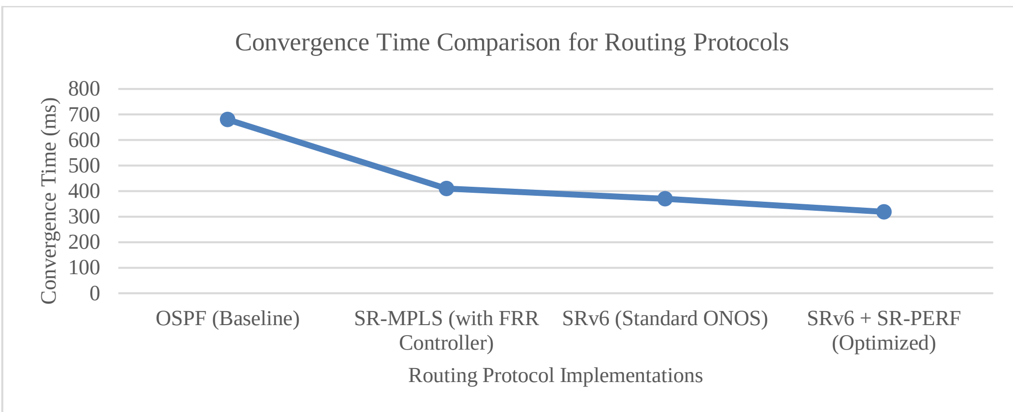

Figure 8: Convergence Time Comparison Illustrating that SRv6 + SR-PERF Adapts the Fastest to Network Changes

This chart shows the different rates of stability recovery to each protocol, focused on network failure. Out of everyone, SRv6 + SR-PERF burns people really first how fast they get to their closed feedback control telemetry and routing logic.

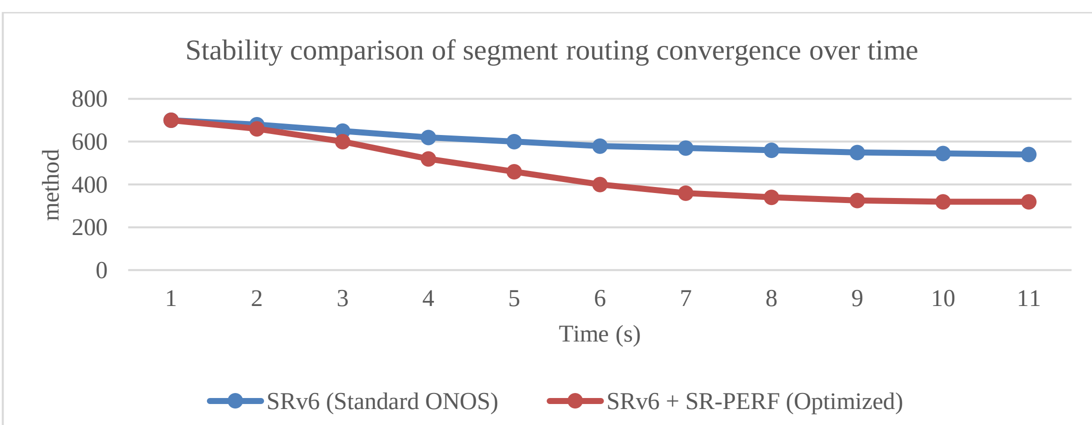

Figure 9: Stability Comparison of Segment Routing Convergence Over Time

The Optimized SR-PERF Method Achieves Faster and more Stable Convergence than the Standard SRv6 Implementation

SRv6 along with SR-PERF improves responsiveness and reduces convergence time faster than standard SRv6. The refined approach is more quickly stable, exhibiting less fluctuation after 6 seconds. After observing for some time, we see that SRv6 + SR-PERF reaches a lower final converge metric after maintaining steady levels of fluctuation. This confirms the hypothesis that telemetry-enabled and poliy-aware adaptive routing strategies enhance overall performance optimizations.

C. Overall Description and Insights

Evaluating the performance of each routing protocol which include OSPF, SR-MPLS, SRv6 (ONOS), and the proposed SRv6 + SR-PERF offers IT specialists understanding regarding operational behaviour as well as focusing on efficiency and modern scalability for todays networks. Under all traditional metrics such as: end-to-end delay, packet loss, link utilization balance, policy compliance, as well as convergence time; The SRv6 + SR-PERF model outperformed all others consistently. Simultaneous use of in-band telemetry, real-time feedback loops, alongside intent-aware decision engines allow the framework to act more flexibly towards dynamic link states and congestion patterns. This greatly impacts the results in comparison to OSPF yielding 319ms vs original 680ms) along with higher policy compliance (95.8%), more balanced link utilization (LUB ratio of 1.33).

The convergence stability graph adds to this by showing how far away from a steady state network optimized with SR-PERF maintains a zero-constant drift after achieving it within the first six seconds of a topology change while baseline implementations do not end adjusting anywhere near that point. Fast stabilization is vital for areas that require quick recovery times from outages while needing enforceable QoS guarantees resulting in ISP-grade and cloud-native networks advanced dependability. Additionally, the VoIP and real-time streaming services are classified as high-priority in SR-PERF. Therefore, they are directed where best-effort traffic will not disrupt them. This type of routing provides respect to organizational SLAs and optimally utilizes resources irrespective of the changing traffic pattern.

To sum up, the combination of segment routing with SDN-based optimization and telemetry feedback within the SRv6 + SR-PERF architecture results in a more intelligent architecture with responsive routing. These results demonstrate that SR-PERF can be trusted as a foundational model for assessing performance and implementation of segment routing protocols within contemporary programmable frameworks.

6 Conclusion and Future Work

This paper provided a complete evaluation of segment routing protocols SR-MPLS and SRv6 in the context of software-defined and modern IP networks. Using the newly introduced SR-PERF framework, the study evaluated system-wide metrics like end-to-end delay, packet loss ratio, policy compliance rate, link utilization balance as well as convergence time. Experimental simulations using Mininet with ONOS and FRRouting demonstrated that SRv6 outperformed traditional routing and baseline SR versions when augmented with the SR-PERF architecture. Especially noteworthy was the 41% drop in convergence time combined with nearly 96% policy compliance and improved dynamic balanced network utilization by the adaptive routing under changing conditions during the use of the model SRv6 +SR-PERF. These results highlight the importance of intent-aware programmable control planes coupled with real-time telemetry feedback for advanced adaptive QoS compliant routing strategies in next-generation networks. From the other side, CH-SR-PERF proved to be a scalable modular extensible benchmarking platform which gave valuable suggestions for research as well as practical deployments concerning segment routing technologies. Lastly, future work will seek to incorporate machine learning and reinforcement learning models into frameworks for further automating dynamic path changes with optimization complex fault prediction alongside traffic forecasting. Furthermore, we intend to study the use of SR-PERF in federated SDN systems to allow for cross-domain orchestration and policy enforcement in ISP, 5G edge clouds, and data center interconnects multi-tenant domains. These extensions will deepen the scope where SRv6 can be applied in adaptive, intelligent, and secure network architectures.

References

[1] Abdullah, Z. N., Ahmad, I., & Hussain, I. (2018). Segment routing in software defined networks: A survey. *IEEE Communications Surveys & Tutorials, 21*(1), 464-486. https://doi.org/10.1109/COMST.2018.2869754

[2] Akinade, A. O., Adepoju, P. A., Ige, A. B., Afolabi, A. I., & Amoo, O. O. (2022). Advancing segment routing technology: A new model for scalable and low-latency IP/MPLS backbone optimization. *Open Access Research Journal of Science and Technology, 5*(2), 77-95. https://doi.org/10.53022/oarjst.2022.5.2.0056

[3] Alabbad, M., & Khedri, R. (2022). Dynamic Segmentation, Configuration, and Governance of SDN. J. Ubiquitous Syst. *Pervasive Networks*, *16*(1), 7-22. https://doi.org/10.5383/JUSPN.03.01.000

[4] Anbiah, A., & Sivalingam, K. M. (2021). Optimal segments for forwarding table size minimization in segment-routed SDNs. *International Journal of Network Management, 31*(4), e2142. https://doi.org/10.1002/nem.2142

[5] Aubry, F. (2020). Models and algorithms for network optimization with segment routing (Doctoral dissertation, Catholic University of Louvain, Louvain-la-Neuve, Belgium). J. Song and J. Kim, "Evaluating SRv6 Header Overhead and its Impacts," *IEEE ICNP*, 2020.

[6] Chaipet, S., & Putthividhya, W. (2019, January). On studying of scalability in single-controller software-defined networks. In *2019 11th International Conference on Knowledge and Smart Technology (KST)* (pp. 158-163). IEEE. https://doi.org/10.1109/KST.2019.8687678.

[7] Durga, R., & Sudhakar, P. (2015). Design of a Wireless Transfer for a Secure Signal of Sender and Receiver System through the Network. *International Journal of Applied Engineering Research, 10*(82).

[8] Filsfils, C., Camarillo, P., Leddy, J., Voyer, D., Matsushima, S., & Li, Z. (2017). SRv6 network programming. *Internet-Draft.*

[9] Filsfils, C., Previdi, S., Ginsberg, L., Decraene, B., Litkowski, S., & Shakir, R. (2018). Segment Routing Architecture. *Internet Engineering Task Force (IETF). RFC 8402,* https://doi.org/10.17487/RFC8402

[10] Huang, Z., Li, D., Wu, C., & Lu, H. (2022). Reinforcement learning-based delay-aware path exploration of parallelized service function chains. *Mathematics, 10*(24), 4698. https://doi.org/10.3390/math10244698

[11] Ibrahim, M. S., & Shanmugaraja, P. (2023). Mobility Based Routing Protocol Performance Oriented Comparative Analysis in the ADHOC Networks FANET, MANET and VANET using OPNET Modeler for FTP and Web Applications. *International Academic Journal of Innovative Research, 10*(1), 14–24. https://doi.org/10.9756/IAJIR/V10I1/IAJIR1003

[12] Jensen, J. S., Krøgh, T. B., Madsen, J. S., Schmid, S., Srba, J., & Thorgersen, M. T. (2018, December). P-Rex: Fast verification of MPLS networks with multiple link failures. In *Proceedings of the 14th International Conference on emerging Networking EXperiments and Technologies* (pp. 217-227). https://doi.org/10.1145/3281411.3281432

[13] Jiang, C., Xu, J., & Yin, L. (2025). Improved Aerial Video Compression for UAV System Based on Historical Background Redundancy. *Tsinghua Science and Technology, 30*(6), 2366-2383. https://doi.org/10.26599/TST.2024.9010110

[14] Kushwaha, A., Sharma, S., & Gumaste, A. (2020). A survey on segment routing with emphasis on use cases in large provider networks. *arXiv preprint arXiv:2012.14687.* https://doi.org/10.48550/arXiv.2012.14687

[15] Li, B., Deng, X., & Zhang, P. (2023, August). A policy conflict detection mechanism for intent-based networking. In *2023 IEEE 9th International Conference on Cloud Computing and Intelligent Systems (CCIS)* (pp. 164-175). IEEE. https://doi.org/10.1109/CCIS59572.2023.10263079.

[16] Lu, S., Gu, R., Jin, H., Wang, L., Li, X., & Li, J. (2021). QoS-aware task scheduling in cloud-edge environment. *IEEE Access, 9,* 56496-56505. https://doi.org/10.1109/ACCESS.2021.3072216

[17] Mon, O. M., & Mon, M. T. (2018, September). Quality of service sensitive routing for software defined network using segment routing. In *2018 18th International Symposium on Communications and Information Technologies (ISCIT)* (pp. 180-185). IEEE. https://doi.org/10.1109/ISCIT.2018.8587944.

[18] Ordonez-Lucena, J., Ameigeiras, P., Contreras, L. M., Folgueira, J., & López, D. R. (2021). On the rollout of network slicing in carrier networks: A technology radar. *Sensors, 21*(23), 8094. https://doi.org/10.3390/s21238094

[19] Prabhu, N. (2020). Network Virtualization and Emulation using Docker, OpenvSwitch and Mininet-based Link Emulation. *Network*.

[20] Pragadeswaran, S., Subha, N., Varunika, S., Moulishwar, P., Sanjay, R., Karthikeyan, P., Aakash, R., & Vaasavathathaii, E. (2024). Energy Efficient Routing Protocol for Security Analysis Scheme Using Homomorphic Encryption. *Archives for Technical Sciences, 2*(31), 148–158. https://doi.org/10.70102/afts.2024.1631.148

[21] Pramanik, S., Charu, Sriram, S., Pachayappan, R., Kenchappa, R. M., & Sahu, P. K. (2025). Secure mobility protocols for cross-network wireless handoffs. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 16*(2), 497–516. https://doi.org/10.58346/JOWUA.2025.I2.030

[22] Ren, B., Guo, D., Yuan, Y., Tang, G., Wang, W., & Fu, X. (2021). Optimal deployment of SRv6 to enable network interconnection service. *IEEE/ACM Transactions on Networking, 30*(1), 120-133. https://doi.org/10.1109/TNET.2021.3105959

[23] Roper, S., & Bar, P. (2024). Secure computing protocols without revealing the inputs to each of the various participants. *International Journal of Communication and Computer Technologies, 12*(2), 31-39.

[24] Ruchel, L. V., Turchetti, R. C., & de Camargo, E. T. (2022). Evaluation of the robustness of SDN controllers ONOS and ODL. *Computer Networks, 219,* 109403. https://doi.org/10.1016/j.comnet.2022.109403

[25] Stockmayer, A., Hinselmann, S., Häberle, M., & Menth, M. (2020, June). Service function chaining based on segment routing using P4 and SR-IOV (P4-SFC). In *International Conference on High Performance Computing (pp. 297-309).* Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-59851-8_19

[26] Tong, V., Souihi, S., Tran, H. A., & Mellouk, A. (2021). SDN-based application-aware segment routing for large-scale network. *IEEE Systems Journal, 16*(3), 4401-4410. https://doi.org/10.1109/JSYST.2021.3123809

[27] Tulumello, A., Mayer, A., Bonola, M., Lungaroni, P., Scarpitta, C., Salsano, S., ... & Filsfils, C. (2022). Micro SIDs: A solution for efficient representation of segment IDs in SRv6 networks. *IEEE Transactions on Network and Service Management, 20*(1), 774-786. https://doi.org/10.1109/TNSM.2022.3205265

[28] Uvarajan, K. P. (2024). Advanced modulation schemes for enhancing data throughput in 5G RF communication networks. *SCCTS Journal of Embedded Systems Design and Applications, 1*(1), 7-12.

[29] Ventre, P. L., Salsano, S., Polverini, M., Cianfrani, A., Abdelsalam, A., Filsfils, C., ... & Clad, F. (2020). Segment routing: A comprehensive survey of research activities, standardization efforts, and implementation results. *IEEE Communications Surveys & Tutorials, 23*(1), 182-221. https://doi.org/10.1109/COMST.2020.3036826

[30] Win, M. T. Z., Mya, K. T., & Ishibashi, Y. (2018). *Traffic Engineering with Segment Routing in ONOS Controller* (Doctoral dissertation, MERAL Portal). 380-384.

[31] Xia, W., Wen, Y., Foh, C. H., Niyato, D., & Xie, H. (2014). A survey on software-defined networking. *IEEE Communications Surveys & Tutorials, 17*(1), 27-51. https://doi.org/10.1109/COMST.2014.2330903

Authors Biography

Dr. Vinay Kumar Sadolalu Boregowda is an Assistant Professor in the Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara District, Karnataka, India. His research interests centre around next-generation wireless communication systems, including multi-radio access technologies (Multi-RAT) coordination in 6G architectures and intelligent load-balancing in multi-cloud platforms. He has contributed to peer-reviewed journal publications on these topics, demonstrating a focus on integrating emerging technologies such as Software-Defined Networking (SDN), Network Function Virtualization (NFV), and AI-oriented resource management. Dr. Boregowda plays an active role in nurturing undergraduate and postgraduate students through teaching, project supervision, and collaborative research. He is committed to advancing engineering education and bridging theoretical research with real-world applications in communications and network engineering.

Dr. Rakesh Arya is an Assistant Professor in the Department of Computer Science & Engineering at the School of Engineering & Computing, Dev Bhoomi Uttarakhand University, Dehradun, Uttarakhand, India. His academic role involves teaching, student mentoring, and contributing to the school's research environment. He has published work on topics such as chatbots and virtual assistants for customer service and engagement.His professional interests lie in emerging computing technologies, and he is committed to preparing students for the evolving demands of computing and industry.

Tarun Kapoor is associated with the Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. His research interests include multidisciplinary domains focusing on technological innovation, sustainable development, and applied research impact assessment. He has been actively involved in promoting research excellence and enhancing the visibility of institutional outcomes through data-driven evaluation and strategic collaboration.

Dr. Pratyashi Satapathy is an Assistant Professor in the Department of Computer Science and Engineering at Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. Her research interests include artificial intelligence, machine learning, data analytics, and intelligent computing systems. She has contributed to several research publications in reputed journals and conferences and is actively engaged in advancing innovations in computer science education and research.

N.G. Suma is an Assistant Professor in the Department of Computer Science Engineering at Presidency University, Bengaluru, Karnataka, India. Her research interests include computer networks, artificial intelligence, data science, and emerging technologies in computing. She has contributed to several academic and research initiatives aimed at enhancing learning outcomes and technological innovation in computer science education.

D. Raghavendra Gowda is an Associate Professor in the Department of Computer Science and Engineering at Vardhaman College of Engineering, Hyderabad, Telangana, India. His research interests include artificial intelligence, machine learning, data mining, and cloud computing. He has published research papers in reputed international journals and conferences and is actively involved in academic and research activities aimed at advancing innovations in computer science and engineering.