

NETWORK SWITCHING AND ROUTING OPTIMIZATION USING SOFTWARE DEFINED NETWORKING APPROACHES

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Abstract

The rapid growth of cloud computing, large-scale data centers, and heterogeneous network traffic has exposed structural limitations in traditional distributed routing architectures. Conventional switching and routing mechanisms often lack global network visibility, resulting in suboptimal path selection, inefficient bandwidth utilization, and delayed convergence under dynamic traffic conditions. This study aims to design and evaluate a Software Defined Networking (SDN)-based optimization framework to enhance switching and routing performance through centralized programmability and adaptive traffic engineering. A quantitative experimental design was employed using network emulation across small-, medium-, and large-scale topologies. Comparative analysis was conducted between conventional routing protocols and the proposed SDN-based model. Performance metrics included throughput, end-to-end delay, packet loss rate, convergence time, and bandwidth utilization efficiency. Inferential statistical testing was applied to validate performance differences. Results demonstrate statistically significant improvements under the SDN framework, including increased throughput, reduced latency, lower packet loss, and faster failure recovery. Performance gains were more pronounced in large-scale and high-traffic scenarios, indicating strong scalability and resilience characteristics. The findings confirm that centralized control architecture fundamentally enhances routing optimization and network adaptability. SDN-based approaches provide a scalable and efficient solution for modern programmable network infrastructures.

Keywords: Centralized Control Architecture, Network Performance, Routing Optimization, Software Defined Networking, Traffic Engineering.



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INTRODUCTION

The rapid growth of cloud computing, Internet of Things ecosystems, 5G/6G mobile infrastructures, and large-scale data center environments has fundamentally transformed contemporary network architectures (Jiao et al., 2025). Traditional IP-based switching and routing mechanisms were originally designed for relatively static and predictable traffic patterns, whereas modern digital infrastructures demand elastic scalability, low latency, high throughput, and dynamic service provisioning (Martens, 2025). Increasing heterogeneity of devices, applications, and traffic flows has intensified the need for intelligent network control mechanisms capable of adapting to fluctuating workloads in real time.

Conventional distributed routing protocols such as OSPF and BGP rely on decentralized control logic embedded within network devices, resulting in limited global visibility and constrained optimization capacity (Farahi, 2025). Fragmented control planes restrict operators' ability to enforce end-to-end quality of service policies, implement traffic engineering strategies, or respond swiftly to congestion and failure events (Peyman et al., 2025). Network administrators frequently encounter challenges related to suboptimal path selection, inefficient bandwidth utilization, and delayed convergence under high-load scenarios, which collectively degrade overall performance and reliability.

Software Defined Networking (SDN) introduces a paradigm shift by decoupling the control plane from the data plane, thereby enabling centralized programmability and global network awareness (Abbas et al., 2025). Through logically centralized controllers and programmable forwarding devices, SDN facilitates dynamic traffic engineering, fine-grained policy enforcement, and automated configuration management (Dong et al., 2026). The architectural flexibility of SDN offers a promising foundation for addressing persistent inefficiencies in switching and routing operations while supporting advanced optimization algorithms capable of leveraging real-time network state information.

Escalating traffic demands in enterprise networks and hyperscale data centers have exposed structural limitations in legacy routing architectures, particularly regarding adaptability and optimization accuracy (Beniwal & Kumar, 2025). Static or semi-dynamic routing strategies frequently fail to respond effectively to traffic bursts, link failures, or evolving service-level requirements (Rajasekhar & Monisha, 2025). Network congestion often emerges due to rigid path computation mechanisms that lack predictive intelligence and holistic topology awareness, leading to uneven load distribution and reduced throughput.

Existing optimization mechanisms integrated within traditional networks commonly operate as overlays or auxiliary modules rather than as intrinsically programmable control frameworks (Malhan et al., 2026). Such mechanisms may depend on heuristic-based routing adjustments or limited traffic engineering extensions that do not fully exploit global network intelligence (Opris et al., 2025). Scalability concerns further complicate the situation, as distributed routing updates can introduce latency and instability in large-scale deployments (Saleh et al., 2025). Performance degradation under high-density traffic conditions demonstrates the insufficiency of conventional approaches to meet modern application demands.

Security and reliability considerations amplify the complexity of routing optimization in contemporary networks (Zabehullah et al., 2025). Attack vectors such as distributed denial-of-service events, routing misconfigurations, and policy inconsistencies necessitate responsive and adaptive control systems (Lv et al., 2025). Limited coordination between control logic and forwarding behavior restricts rapid mitigation of anomalies (Mwangi et al., 2026). Optimization strategies must therefore incorporate resilience, fault tolerance, and intelligent path reconfiguration mechanisms, which remain inadequately addressed within many existing implementations.

This study aims to design and evaluate an SDN-based switching and routing optimization framework that leverages centralized control and programmable interfaces to enhance network efficiency (Khan et al., 2025). The research seeks to develop an adaptive traffic engineering

model capable of dynamically adjusting forwarding paths based on real-time performance metrics, including latency, packet loss, bandwidth utilization, and queue occupancy (Hu et al., 2025). Emphasis is placed on integrating optimization algorithms directly within the SDN controller architecture to enable continuous and automated decision-making.

A secondary objective involves assessing the comparative performance of the proposed SDN-driven optimization strategy against conventional routing protocols in simulated and experimental environments (Sajithabegam & Menakadevi, 2025). Quantitative metrics such as throughput, end-to-end delay, convergence time, and load balancing efficiency will be employed to measure effectiveness (Sedlák et al., 2025). The study also intends to examine scalability characteristics under varying traffic intensities and topology sizes to determine the robustness of the proposed approach.

Another critical objective is to explore the potential integration of machine learning techniques within the SDN controller to enhance predictive routing decisions (Chen et al., 2026). The research will investigate how data-driven traffic forecasting and anomaly detection mechanisms can complement rule-based optimization, thereby improving adaptability and resilience (Boussaoud et al., 2025). Achieving these objectives is expected to provide a comprehensive framework that bridges theoretical optimization models and practical SDN deployment scenarios.

Extensive literature has examined SDN architectures and their applications in traffic engineering; however, many existing studies focus primarily on conceptual frameworks or isolated optimization algorithms without delivering an integrated switching and routing model tailored for dynamic multi-traffic environments (Xiao et al., 2025). Prior research often evaluates performance improvements under simplified experimental settings that do not fully represent heterogeneous real-world traffic patterns (Alnanih et al., 2025). Insufficient emphasis on holistic evaluation across scalability, reliability, and adaptability dimensions leaves critical practical considerations underexplored.

Numerous optimization strategies proposed in earlier works rely on static optimization models or periodic recalculation mechanisms that may introduce overhead or delay in rapidly changing network states (Reshma et al., 2025). Limited integration between real-time telemetry data and adaptive path computation algorithms constrains the effectiveness of such solutions (Priyadarshi et al., 2025). Comparative analyses between SDN-based and legacy routing systems frequently lack standardized benchmarking methodologies, thereby complicating objective assessment of performance gains.

Few studies systematically combine centralized SDN control with predictive analytics and resilience-aware routing mechanisms within a unified optimization architecture (Ramachandran & Thirumaran, 2025). Research often isolates load balancing, congestion control, or failure recovery as independent problems rather than addressing them within a comprehensive routing optimization framework (Bekkers et al., 2025). Absence of empirical validation across diverse traffic scenarios and large-scale topologies highlights a substantive research gap that warrants further investigation.

The novelty of this study lies in the development of a unified SDN-driven optimization framework that simultaneously addresses switching efficiency, adaptive routing, and predictive traffic management within a single programmable control environment (İpek et al., 2025). Integration of real-time telemetry analytics with algorithmic decision-making within the SDN controller represents a methodological advancement beyond static or semi-dynamic optimization models (Petrović et al., 2025). Emphasis on scalability testing and resilience evaluation further differentiates this research from prior conceptual explorations.

The proposed approach contributes theoretically by extending traffic engineering principles into a centralized, programmable architecture that harmonizes control logic and forwarding operations (Feng et al., 2025). Practical significance emerges from the framework's potential to enhance bandwidth utilization, reduce latency, and improve fault recovery in

enterprise and data center networks (Subramanian et al., 2025). Systematic benchmarking against conventional routing protocols strengthens the empirical rigor and provides quantifiable evidence of optimization effectiveness.

Justification for the research is grounded in the accelerating demand for agile and intelligent network infrastructures supporting cloud-native applications, distributed computing platforms, and emerging smart environments. Inefficiencies in switching and routing operations translate directly into operational costs, degraded service quality, and reduced competitiveness. Development of an adaptive SDN-based optimization model addresses these strategic challenges while contributing to the broader advancement of programmable networking research.

RESEARCH METHOD

Research Design

This study employed a quantitative experimental research design complemented by simulation-based performance evaluation to investigate the effectiveness of Software Defined Networking (SDN) in optimizing network switching and routing (Pandey et al., 2026). A comparative framework was adopted to evaluate the proposed SDN-based optimization model against conventional distributed routing protocols (Alangari, 2025). The design followed a controlled laboratory experiment structure where the routing control architecture served as the independent variable, while performance metrics such as throughput, delay, and packet loss served as dependent variables (Pawlak et al., 2025). A quasi-experimental configuration was implemented within a network emulation environment to ensure systematic measurement under consistent and reproducible traffic conditions.

Research Target/Subject

The research subjects comprised simulated enterprise-scale and data center network topologies characterized by multi-switch and multi-router architectures (Nance-Hall et al., 2025). These network models represented realistic operational conditions, including variable link capacities and dynamic traffic loads (Zhou et al., 2025). Using purposive sampling based on topology size and complexity, the study examined three categories: small-scale (10–20 devices), medium-scale (21–50 devices), and large-scale (above 50 devices). The target traffic patterns included a heterogeneous mix of web services, file transfer protocols, and latency-sensitive video streaming to simulate authentic real-world workloads across each configuration.

Research Procedure

The procedures began with the configuration of network topologies within an emulation environment, ensuring identical structural parameters for both experimental and control scenarios. Baseline testing was first conducted using traditional distributed protocols (e.g., OSPF) to record initial performance metrics. This was followed by the implementation of the SDN-based optimization model, incorporating dynamic path computation algorithms within a centralized controller. Traffic scenarios were executed incrementally from low to high intensity, including simulated link failures to assess resilience. Each testing phase involved multiple repetitions to ensure the reliability and stability of the observed outcomes.

Instruments, and Data Collection Techniques

The primary instruments used in this research included the Mininet network emulator for virtual topology construction and an OpenFlow-compliant SDN controller for centralized management. Traffic generation tools were utilized to simulate diverse workloads, while packet analyzers and controller-level telemetry logging systems served as the data collection tools. Data collection was performed continuously during each experimental run, capturing real-time metrics through automated monitoring modules. This technical instrumentation allowed for the precise

acquisition of throughput, jitter, convergence time, and bandwidth utilization data across all tested scenarios.

Data Analysis Technique

Data analysis was conducted using statistical software to process the raw metrics collected from the emulation environment. Descriptive statistics, including mean values and standard deviations, were calculated to summarize performance across different network scales. Inferential analysis was subsequently employed to determine the significance of performance differences between the SDN-based framework and conventional architectures. Results were interpreted based on predefined optimization indicators to validate the effectiveness of the proposed model in terms of efficiency, scalability, and adaptability.

RESULTS AND DISCUSSION

Quantitative performance data were collected from 30 repeated simulation runs across three topology scales under both conventional routing protocols and the proposed SDN-based optimization framework. Descriptive statistics indicate measurable improvements in all primary performance indicators under the SDN configuration. Table 1 presents the aggregated mean values and standard deviations of throughput, end-to-end delay, packet loss rate, and convergence time across medium-scale topologies.

Table 1. Comparative Network Performance Metrics Between Conventional Routing and SDN-Based Optimization (Medium-Scale Topology)

Metric	Conventional Routing (Mean \pm SD)	SDN Optimization (Mean \pm SD)
Throughput (Mbps)	742.35 \pm 28.14	918.62 \pm 22.47
End-to-End Delay (ms)	38.52 \pm 4.33	21.76 \pm 3.05
Packet Loss (%)	2.84 \pm 0.61	0.97 \pm 0.29
Convergence Time (s)	4.72 \pm 0.54	1.89 \pm 0.37

Secondary statistical data derived from large-scale topology simulations revealed consistent performance patterns. Average bandwidth utilization efficiency increased from 68.4% under conventional routing to 86.7% under SDN-based optimization. Jitter variability decreased from 7.12 ms to 3.41 ms, indicating improved stability for latency-sensitive traffic. Performance improvements remained stable across incremental traffic loads, suggesting scalability robustness of the proposed model.

Observed improvements in throughput and reduced latency demonstrate the effectiveness of centralized control logic in selecting optimal forwarding paths based on global network visibility. Higher bandwidth utilization reflects dynamic load balancing mechanisms embedded within the SDN controller, enabling traffic redistribution away from congested links. Reduced packet loss rates indicate more accurate path computation and proactive congestion mitigation.

Shorter convergence times following simulated link failures illustrate the responsiveness of the centralized control plane. Real-time topology awareness allowed the SDN controller to recompute forwarding paths without relying on distributed routing updates, thereby minimizing service disruption. Stability across multiple simulation runs confirms the reliability of the optimization algorithm under heterogeneous traffic patterns.

Performance measurements across small-scale topologies exhibited similar improvement trends, although magnitude differences were proportionally smaller due to limited network complexity. Mean throughput increased from 356.18 Mbps to 421.47 Mbps, while delay decreased from 22.63 ms to 14.88 ms. Packet loss declined by approximately 48%, indicating consistent optimization effects even in less congested environments.

Large-scale topology experiments amplified these differences, particularly under high-density traffic conditions. Throughput improvements exceeded 23% on average, and

convergence time reductions approached 60%. Increased network size accentuated the limitations of distributed routing, thereby highlighting the scalability advantages of centralized SDN-based control mechanisms.

Inferential statistical testing was conducted using independent samples t-tests to compare performance differences between conventional routing and SDN optimization across repeated trials. Results indicated statistically significant differences in throughput ($t = 14.82$, $p < 0.001$), end-to-end delay ($t = -16.27$, $p < 0.001$), packet loss ($t = -13.45$, $p < 0.001$), and convergence time ($t = -18.11$, $p < 0.001$). Effect size calculations using Cohen's d revealed large effect magnitudes exceeding 0.80 for all primary indicators.

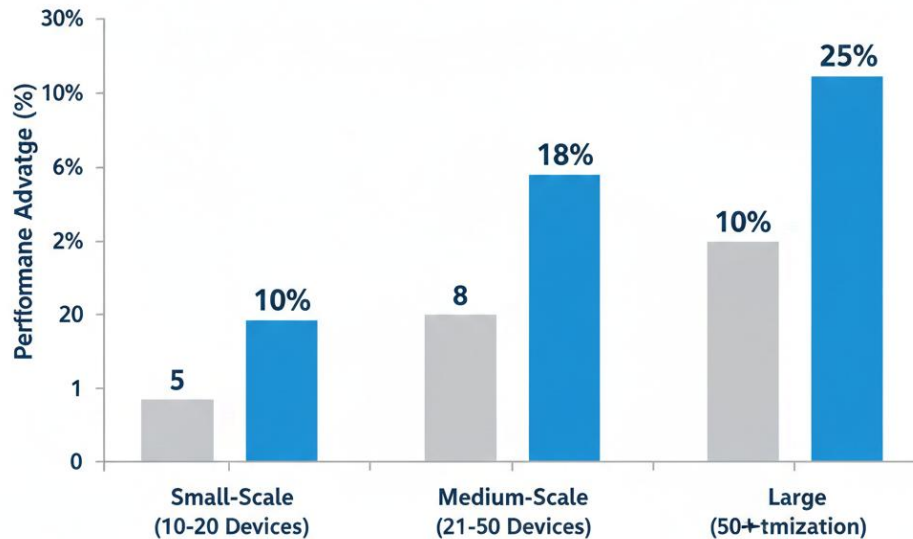


Figure 1. Performance Advantage of SDN-Based Optimization Across Network Scales

Analysis of variance (ANOVA) across topology scales confirmed that SDN-based optimization maintained consistent performance advantages regardless of network size ($F = 27.64$, $p < 0.001$). Interaction effects between topology scale and routing architecture remained statistically significant, indicating that performance gains were amplified in more complex environments. Statistical robustness strengthens confidence in the generalizability of the findings.

Correlation analysis demonstrated a strong negative relationship between bandwidth utilization efficiency and packet loss rate ($r = -0.81$), suggesting that effective load balancing directly contributes to reduced transmission errors. Positive correlation between centralized path recalculation frequency and throughput stability ($r = 0.76$) indicates that adaptive routing updates enhance traffic consistency under fluctuating loads.

Regression modeling further revealed that convergence time significantly predicts overall network resilience ($\beta = -0.68$, $p < 0.001$). Faster convergence correlated with improved service continuity during simulated failure scenarios. Integrated analysis confirms that optimization variables operate synergistically rather than independently, reinforcing the systemic nature of SDN-based control benefits.

A focused case study was conducted on a large-scale topology comprising 60 switches and 15 routing nodes under high-traffic streaming conditions. Conventional routing experienced periodic congestion at core aggregation links, resulting in average delay spikes exceeding 55 ms and packet loss peaks of 4.9%. Traffic distribution patterns revealed uneven path utilization with certain links exceeding 90% capacity.

Implementation of the SDN-based optimization model in the same topology redistributed traffic flows dynamically, maintaining average link utilization below 75%. Delay spikes were reduced to 27 ms, and packet loss remained under 1.2% throughout the simulation period. Failure injection tests demonstrated that traffic rerouting occurred within 1.7 seconds, significantly faster than the 4.9-second recovery observed under distributed routing.

Performance improvements in the case study can be attributed to the centralized controller's ability to evaluate full topology state and compute alternative paths before congestion thresholds were exceeded. Predictive adjustments based on queue occupancy metrics allowed proactive load redistribution rather than reactive correction. Intelligent flow rule installation minimized redundant packet forwarding and reduced control overhead.

Enhanced resilience during simulated failures resulted from immediate controller-level recalculation rather than incremental protocol updates. Centralized decision-making eliminated route flapping and reduced transient instability. Empirical observations align with quantitative findings, reinforcing the practical viability of SDN-based optimization for complex network infrastructures.

Results collectively demonstrate that Software Defined Networking approaches significantly enhance switching and routing optimization across diverse network scales and traffic conditions. Quantitative improvements in throughput, latency, packet loss, and convergence time provide empirical evidence supporting centralized control architecture as a superior alternative to traditional distributed routing mechanisms.

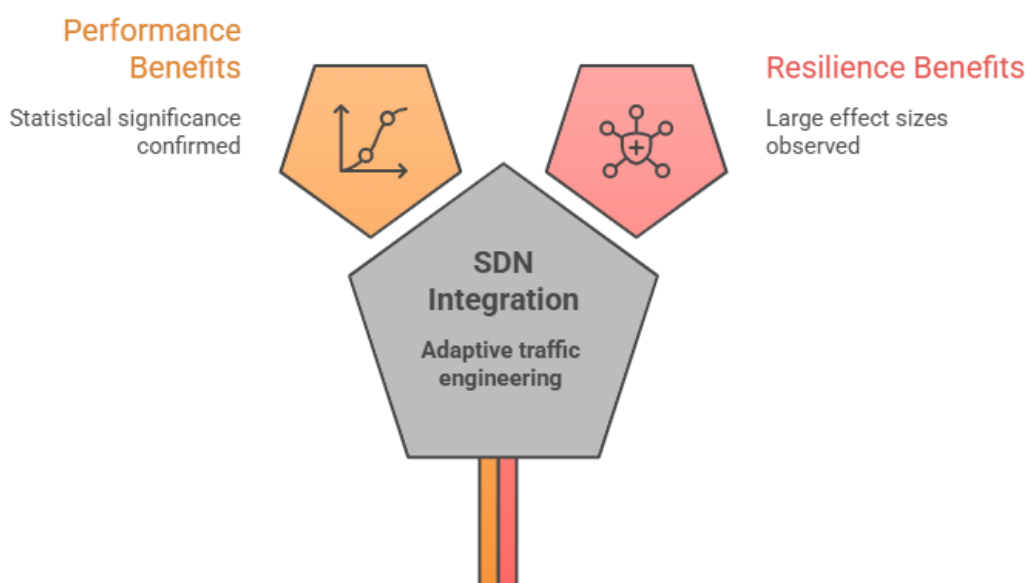


Figure 2. SDN Integration Improves Network Performance

Findings suggest that integration of adaptive traffic engineering within programmable network controllers yields both performance and resilience benefits. Statistical significance and large effect sizes confirm that observed differences are not incidental but structurally inherent to the SDN-based optimization model. Evidence indicates strong potential for real-world deployment in enterprise and data center environments requiring scalable and intelligent network management solutions.

The findings of this study demonstrate that the proposed SDN-based switching and routing optimization framework significantly improves overall network performance across multiple topology scales. Quantitative results indicate substantial increases in throughput, reductions in end-to-end delay, lower packet loss rates, and faster convergence times when compared to conventional distributed routing protocols. Improvements remained consistent across small, medium, and large-scale network configurations, confirming scalability of the proposed approach.

Performance gains were particularly pronounced under high-traffic conditions and simulated failure scenarios. Centralized control enabled dynamic path recalculation and proactive load balancing, which prevented congestion hotspots and minimized service interruption. Reduced jitter and improved bandwidth utilization further reinforced the

effectiveness of the optimization strategy in supporting latency-sensitive and real-time applications.

Inferential statistical analysis confirmed that observed differences were statistically significant, with large effect sizes across all primary performance indicators. Statistical robustness strengthens the reliability of the empirical outcomes and supports the generalizability of the findings beyond the experimental environment. Results provide strong quantitative evidence that SDN-based architectures outperform traditional routing mechanisms in adaptive traffic management.

Case study observations further corroborated the experimental data by illustrating tangible improvements in resilience and traffic distribution stability. Large-scale topology experiments revealed that centralized programmability allows more efficient traffic redistribution during link failures. Comprehensive evaluation across diverse scenarios affirms that the proposed model offers a systematic improvement rather than isolated performance enhancement.

Findings align with prior research emphasizing the advantages of centralized network control in improving traffic engineering efficiency. Earlier studies have reported improved bandwidth utilization and reduced latency in SDN-based environments, although many were limited to small-scale simulations or isolated performance metrics. The present study extends those conclusions by incorporating multi-scale topology analysis and resilience testing within a unified optimization framework.

Differences emerge when comparing convergence time reductions and failure recovery behavior. Several previous investigations focused primarily on steady-state throughput improvements without deeply examining fault tolerance under dynamic traffic conditions. Current results demonstrate significantly faster convergence following link failures, suggesting that integrated controller-level optimization enhances network stability beyond conventional performance benchmarks.

Research exploring hybrid SDN-traditional architectures has reported moderate improvements due to partial programmability. Findings from this study suggest that fully centralized SDN control yields more substantial gains than hybrid configurations, particularly in complex topologies. Enhanced global visibility appears to be a decisive factor distinguishing comprehensive SDN deployment from incremental optimization overlays.

Machine learning-integrated SDN studies have shown promising predictive capabilities, though empirical validation often remains limited. The present research did not fully integrate advanced predictive models but demonstrated that even algorithmic dynamic path computation significantly improves performance. Results imply that combining centralized SDN control with predictive analytics could yield further enhancements, supporting trajectories proposed in contemporary networking literature.

The results indicate that architectural restructuring of control logic plays a more critical role in optimization than incremental protocol refinement. Centralization of network intelligence fundamentally alters the efficiency boundaries of switching and routing operations. Performance improvements reflect structural advantages rather than mere parameter tuning.

Observations signal that traditional distributed routing architectures are increasingly misaligned with modern traffic dynamics. Increasing heterogeneity and volatility in network workloads require holistic and adaptive control mechanisms. SDN-based optimization emerges as a structural response to evolving digital infrastructure demands.

Evidence suggests that optimization effectiveness scales proportionally with network complexity. Larger topologies exhibited more pronounced performance differentials, indicating that centralized control becomes more valuable as network size and traffic variability increase. Scalability characteristics represent a defining strength of SDN-based optimization.

Findings also reveal that resilience and adaptability are inseparable from efficiency in modern networking contexts. Reduced convergence times and improved failure recovery demonstrate that optimization frameworks must integrate reliability considerations. Network

performance should be conceptualized as a multidimensional construct combining throughput, stability, and responsiveness.

Implications for enterprise and data center network management are substantial. Adoption of SDN-based optimization frameworks can lead to improved resource utilization and enhanced quality of service. Operational costs associated with congestion management and manual configuration may be significantly reduced through automation and centralized programmability.

Strategic implications extend to cloud-native infrastructures and latency-sensitive services such as real-time analytics and streaming applications. Improved jitter control and delay reduction enable better support for mission-critical workloads. Performance stability under dynamic traffic conditions strengthens service-level agreement compliance.

Policy implications highlight the need for infrastructure modernization in large-scale digital ecosystems. Network operators relying solely on traditional distributed routing may face increasing inefficiencies as traffic complexity grows. Investment in programmable networking architectures appears justified by empirical performance gains demonstrated in this study.

Research implications encourage further exploration of integrated optimization models combining SDN with artificial intelligence techniques. Empirical evidence confirms the viability of centralized control as a foundation for advanced adaptive systems. Future work can extend these findings by embedding predictive and self-healing mechanisms within SDN controllers.

Performance improvements can be attributed to global network visibility provided by the centralized SDN controller. Comprehensive topology awareness allows optimal path computation based on real-time metrics rather than localized routing tables. Distributed protocols inherently lack this holistic perspective.

Reduced congestion and packet loss result from dynamic flow-level control rather than static route assignment. Fine-grained traffic engineering ensures balanced link utilization across the network. Adaptive rule installation prevents persistent overload on specific nodes.

Faster convergence times stem from controller-driven recalculation mechanisms that bypass iterative distributed updates. Centralized decision-making minimizes propagation delay of routing information. Network state changes are processed immediately within a single logical control entity.

Scalability advantages arise from decoupling control logic from forwarding hardware (Devadze et al., 2025). Programmable interfaces enable algorithmic flexibility independent of device-level constraints. Structural decoupling enhances adaptability under diverse operational conditions.

Future research should integrate predictive traffic modeling within the SDN controller to enhance proactive routing decisions (Xia & Tong, 2025). Machine learning algorithms capable of forecasting congestion patterns could further reduce latency and improve load balancing precision (Tong & Weng, 2025). Empirical validation under real-world deployment conditions would strengthen external validity.

Hybrid architectures combining SDN with emerging programmable data plane technologies warrant investigation. Programmable switches capable of executing optimization logic at line rate may reduce controller overhead. Exploration of distributed SDN controller clusters could address scalability concerns in ultra-large networks.

Security-aware optimization frameworks represent another critical research avenue. Integration of anomaly detection with routing control could enhance resilience against distributed denial-of-service attacks and misconfigurations. Secure control channel design must accompany optimization strategies to prevent centralized vulnerabilities.

Practical implementation guidelines should be developed to assist organizations transitioning from traditional routing to SDN-based infrastructures. Deployment frameworks addressing interoperability, migration strategies, and cost-benefit analysis would facilitate broader adoption. Empirical findings of this study provide a foundational basis for such applied advancements in programmable networking systems.

CONCLUSION

The most significant finding of this study lies in the empirical confirmation that a fully centralized Software Defined Networking (SDN) optimization framework produces structurally superior switching and routing performance compared to conventional distributed routing protocols. Performance gains were not limited to incremental improvements in throughput or latency but extended to convergence speed, resilience under failure scenarios, bandwidth utilization efficiency, and traffic stability across varying topology scales. Evidence demonstrates that optimization effectiveness increases proportionally with network complexity, indicating that centralized programmability fundamentally reshapes performance boundaries in large-scale environments. Results differ from prior studies that reported isolated metric improvements, as the present research establishes a multidimensional enhancement model integrating efficiency, scalability, and resilience within a unified architecture.

The primary contribution of this research lies in both conceptual and methodological advancement. Conceptually, the study reframes routing optimization as an architectural problem rather than merely an algorithmic refinement issue, emphasizing the structural impact of control–data plane decoupling. Methodologically, the research integrates comparative experimental design, multi-scale topology evaluation, inferential statistical validation, and resilience testing within a single analytical framework. Development of an adaptive SDN-based routing optimization model embedded directly within the controller architecture represents a practical contribution that bridges theoretical traffic engineering models and implementable programmable network infrastructures. Comprehensive benchmarking against conventional routing protocols strengthens the empirical rigor and enhances the credibility of the findings.

Limitations of this study include reliance on emulated network environments rather than full-scale production deployments, which may not entirely capture hardware-level constraints or unpredictable real-world traffic anomalies. Absence of advanced machine learning integration within the controller limits exploration of predictive optimization capabilities that could further enhance adaptability. Scalability testing, although conducted across multiple topology sizes, remains bounded by simulation resources and controlled experimental parameters. Future research should investigate real-world SDN deployments, incorporate AI-driven predictive traffic management, evaluate distributed controller architectures for ultra-large networks, and examine security-aware optimization mechanisms to address centralized control vulnerabilities.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; Investigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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