AI-Enabled Optimal Path Selection for QoS-Aware Routing in Software-Defined Networks

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Abstract
The rapid advancement of 5G and Internet of Things (IoT) technologies, there is a growing demand for efficient network management, optimized resource allocation, and robust security mechanisms. This study investigates AI-driven approaches, emphasizing the role of Software-Defined Networking (SDN) and hybrid frameworks in addressing these challenges. It showcases the application of Machine Learning (ML) and Deep Reinforcement Learning (DRL) to enhance Quality of Service (QoS), streamline traffic management, and ensure network scalability. Notable innovations include the Optimized Geographic and Spectrum-based Cluster Routing (OGCSR) protocol for Vehicular Ad Hoc Networks (VANETs), the SMART framework for seamless SDN migration, and the Intelligent Anomaly-aware Network Optimization using Bidirectional Gated Recurrent Unit (IANO-BGRU) model for detecting cloud-based threats. These AI-integrated solutions demonstrate significant improvements in packet delivery rates, reduced latency, and better energy efficiency, underscoring the importance of AI-SDN convergence in developing adaptive and high-performance network infrastructures.

Keywords: Quality of Service, Deep Reinforcement Learning, Machine Learning, Optimized Geographic and Spectrum-based Cluster Routing, Intelligent Anomaly-aware Network Optimization using Bidirectional Gated Recurrent Unit

1. INTRODUCTION

The unprecedented growth of 5G and the in IoT has significantly transformed the landscape of modern communication networks. These advancements, while driving innovation and enabling new applications, have introduced substantial complexity in network performance management [1]. Traditional network architectures often struggle to adapt to the dynamic demands of such environments, including high data rates, ultra-low latency, and massive device connectivity.

The evolution of networking architectures has been significantly influenced by the emergence of SDN, which separates the control and data planes to enable centralized, programmable, and flexible network management. With the rapid growth of 5G, IoT, and edge computing, ensuring QoS across dynamic, heterogeneous environments has become a critical challenge [2].

This review explores a wide spectrum of recent research efforts that address SDN-based QoS optimization using advanced technologies such as ML, DRL, traffic classification, and hybrid network models. The studies span diverse domains—from cloud computing and IoT to vehicular networks and multimedia sensing—focusing on routing efficiency, traffic engineering, security, scalability, and energy optimization.

Collectively, these works highlight innovative methodologies and practical frameworks that drive the development of intelligent, adaptive, and high-performance networks.

The rapid evolution of digital infrastructure, catalyzed by the proliferation of IoT devices, 5G technologies, and cloud-based services, has placed unprecedented demands on modern networks [5]. Traditional network architectures, constrained by rigid protocols and decentralized management, struggle to meet the increasing requirements for scalability, flexibility, security, QoS [7]. In response to these limitations, SDN has emerged as a transformative paradigm, decoupling the control and data planes to enable centralized, programmable network management.

This literature compilation explores the cutting-edge research and innovations shaping SDN-based architectures, with a focus on intelligent routing, traffic engineering, load balancing, and QoS optimization. The diverse studies included here highlight how ML, DRL, and other AI-driven methodologies are being integrated into SDNs to support efficient traffic classification, adaptive routing, fault tolerance, and service-aware scheduling.

One of the central challenges addressed across these works is maintaining high QoS in increasingly heterogeneous environments—ranging from consumer IoT (CIoT) and VANETs to multi-cloud infrastructures and cyber-physical systems (CPS). The Controlled Service Scheduling Scheme (CS3), for instance, leverages regression learning to optimize resource allocation under dynamic conditions, while frameworks like CoopAI-Route and SMART demonstrate the power of cooperative DRL models for scalable and intelligent routing in SDN-enabled, beyond-5G networks [8].

Moreover, hybrid SDN architectures that integrate legacy systems with SDN elements are gaining attention for facilitating incremental migration strategies. These hybrid systems, while promising, also introduce new complexities in traffic management and interoperability, which are being actively addressed through intelligent solutions such as GAho, FLDR, and IANO-BGRU .

Across the surveyed literature, several critical themes emerge:

- The need for dynamic, adaptive routing mechanisms that can respond to real-time traffic changes.
- The importance of intelligent traffic classification and feature extraction to manage large-scale, high-speed networks.
- The growing emphasis on energy efficiency, security, and QoS-aware scheduling in the face of rising data demands and environmental concerns.
- The role of network slicing, serverless architectures, and edge computing in extending SDN capabilities to meet specific application requirements.

Together, these works represent a rich and evolving ecosystem of research that seeks to redefine how modern networks are designed, managed, and optimized. By systematically examining these innovations, this study provides valuable insights into the state-of-the-art techniques and frameworks driving the next generation of high-performance, intelligent, and resilient network infrastructures.

Recent research has focused on the convergence of SDN and AI to tackle issues like traffic congestion, routing inefficiencies, and security vulnerabilities across IoT-enabled infrastructures. Advanced frameworks and protocols, such as the CS3, the SMART SDN migration framework, and the IANO-BGRU security model, demonstrate the potential of AI-driven SDN architectures in optimizing network performance [3]. Additionally, hybrid network environments, such as those incorporating legacy systems with SDN, and challenging domains like VANETs, benefit from specialized routing strategies and traffic engineering solutions.

2. LITERATURE SURVEY

The studies focus on optimizing QoS and network performance in SDN and IoT through machine learning, dynamic load balancing, and deep reinforcement learning. Key protocols like OGCSR, SMART, and IANO-BGRU improve packet delivery, reduce delays, and enhance security. Hybrid models such as HSP and SAG offer scalable, efficient solutions for dynamic systems, with future research needed to address scalability, security, and algorithm improvements for IoT, 5G, and beyond.

Albekairi et al. [4] presents the CS3 for SDNs, enhancing user service by leveraging operational plane differentiation. It uses a routed regression learning model to optimize scheduling based on device capacity, user density, and a maximum routed threshold for plane migrations. CS3 dynamically adjusts thresholds to handle dense IoT requests, ensuring efficient resource allocation. The results show a 13.92% improvement in scheduling rate, an 8.31% increase in service distribution, an 11.58% reduction in delays, and a 1.7% distribution failure rate, demonstrating CS3's effectiveness in boosting SDN performance and managing IoT traffic.

Sahoo et al. [5] examines optimization techniques for enhancing QoS in IoT-aided wireless networks, driven by 5G adoption and the resulting data surge from billions of connected devices. It addresses network overhead issues like energy use, routing, data rates, and security across various IoT networks — IoMobT, IoV, IoF, IoR, IoS, and IoU. The survey categorizes research by issues tackled and strategies used, highlighting trends and solutions to optimize QoS in diverse IoT models.

Kalaivani et al. [6] explores routing strategies in SDN, highlighting the impact of ML techniques on network performance. SDN’s decoupled architecture allows centralized management and flexible routing adjustments, crucial for improving scalability and efficiency. While traditional models rely on heuristic and metaheuristic methods, ML-enhanced approaches offer adaptive solutions to tackle delay, traffic congestion, and resource optimization. The study analyzes various ML-based routing strategies, assessing their benefits, limitations, and future potential, and concludes with recommendations for boosting routing efficiency through advanced techniques.

Mehraban et al.[7] explores Traffic Engineering (TE) and QoS challenges in Hybrid SDN networks, where SDN devices coexist with traditional network devices to address the complexities of migrating from legacy networks. SDN’s separation of Data and Control layers enables centralized management, improving throughput, link utilization, and flow scheduling. Hybrid SDN networks tackle technical, financial, and security challenges while enhancing QoS—measured by latency, jitter, loss, bandwidth, and link utilization. The study reviews various algorithms and mechanisms, including DRL, heuristic algorithms, K path partition, genetic algorithms, SOTE, ROAR, and routing optimization techniques, aiming to ensure high-performance network management.

Dhandapani et al.[8] introduces **CoopAI-Route**, a multi-agent cooperative DRL system designed for beyond 5G networks to enable intelligent, performance-based routing in multi-domain environments. As network slicing becomes essential for meeting the time-sensitive demands of next-generation applications, traditional inter-domain routing methods like BGP struggle with congestion and lack of collaboration between network operators. CoopAI-Route leverages hierarchical SDN and the Distributed Global Topology (DGT) algorithm to enforce network slicing and optimize QoS routes. Using a message-passing multi-agent Twin-Delayed Deep Deterministic Policy Gradient method, it dynamically adapts to changing topologies and link failures. Evaluations show CoopAI-Route outperforms existing approaches in scalability, fault tolerance, and routing efficiency, offering a robust solution for future networks.

Serag et al.[9] explores the integration of SDN and ML to enhance network performance and QoS. SDN's separation of control and data planes enables centralized network management, while ML algorithms, particularly for Traffic Classification (TC), outperform traditional methods by dynamically and adaptively identifying traffic flows. The study highlights how labeled traffic data trains ML models for accurate TC in SDN networks and examines ML's role in improving security through anomaly detection, intrusion detection, and attack mitigation. It also discusses challenges in SDN-ML integration, such as scalability and performance in large-scale networks, identifying research gaps and future directions for optimizing QoS.

Grif et al.[10] analyzes QoS solutions in Software-Defined IoT (SD-IoT) networks, where SDN’s separation of control and data planes enables centralized, flexible traffic and resource management. It explores techniques like QoS routing, dynamic load balancing, real-time traffic classification, and adaptive rule placement, showcasing improvements in routing efficiency and heuristic-based load balancing strategies. The study highlights ongoing challenges, such as scalability issues, and suggests future research directions, including AI integration to enhance network adaptability and tackle the increasing complexity of SD-IoT environments.

Mostafa, B et al. [11] explores how routing protocols in Wireless Sensor Networks (WSNs) address multi-constrained QoS requirements, such as delay, jitter, and packet loss, especially in large networks using multi-hop routing to transmit data to sink nodes. It analyzes protocols like the Routing Protocol for Low-Power and Lossy Networks (RPL), which uses Destination-Oriented Directed Acyclic Graphs (DODAGs) based on single-metric Objective Functions. The study highlights that QoS-constrained routes often form hierarchies rather than simple in-cast trees, requiring multiple DODAGs to support complex QoS needs. To manage the computational complexity of these routes, the paper proposes offloading heavy computation tasks to edge servers, ensuring practical and efficient protocol adaptation.

Bishla, et al. [12] SDN separates network control from data forwarding, enhancing flexibility by isolating network architecture from applications. A hybrid SDN framework allows legacy and SDN protocols to coexist, but managing traffic becomes complex. Segment routing, while effective, introduces control overhead through extra packet headers and faces challenges like network congestion, packet loss, and high energy consumption. To address this, the proposed Gannet artificial humming optimization (GAho) algorithm uses a multi-objective fitness function — considering link quality and flow characteristics — to enable congestion-free routing. Performance analysis shows GAho-based segment routing achieves a delay of 4.24 ms, throughput of 77.61%, jitter of 0.15 seconds, and a packet drop rate of 1.82%.

Wu et al.[13] SDN centralizes control through a controller managing communication between application and data planes. In 5G networks, ensuring service quality, especially for ultra-reliable low-latency communication (URLLC), is critical. This paper proposes a fuzzy logic-based dynamic routing (FLDR) mechanism for SDN-based 5G networks, using normalized throughput, packet delay, and link utilization to calculate path weights and reroute traffic in real-time. Tested on Mininet with added modules for topology discovery, monitoring, and rerouting, FLDR outperforms existing methods in throughput, packet loss rate, and delay under various traffic loads.

Ezechi et al.[14] SDN is transforming Cyber-Physical Systems (CPSs) by combining software flexibility with physical network infrastructures. It enables centralized control, dynamic adaptability, and enhanced security by separating control and data planes, allowing real-time network management. SDN optimizes resource use, boosts network performance, and strengthens security through centralized threat management. Its integration into CPSs supports scalable, resilient systems capable of adapting to changing conditions. However, challenges remain in meeting CPSs' real-time communication demands, such as low latency and high throughput. This chapter explores the benefits, challenges, and opportunities of SDN in CPSs, emphasizing dynamic network management for system resilience and high-performance communication.

Eldhai et al.[15] TC in SDN using ML enhances network management by accelerating Feature Selection (FS) and extracting real-time data for the SDN controller. However, challenges arise due to similar traffic profiles and the added complexity of Stream Learning (SL). To address this, robust statistical flow features are proposed to reduce SDN control plane overhead by enabling online feature extraction, handling concept drift, and processing continuous data streams with minimal resources. This paper introduces the Boruta FS mechanism and three streaming-based TC methods for SDN — Hoeffding Adaptive Trees (HAT), Adaptive Random Forest (ARF), and k-Nearest Neighbor with adaptive sliding window detector (kNN-ADWIN). These methods dynamically manage concept drift and optimize time and memory use. Evaluation using real and synthetic traffic traces shows the Boruta FS technique achieves up to 95% accuracy and 87% in precision, recall, and f-score. The SL techniques maintain up to 85% accuracy, 78% kappa, and 62–88% in precision, recall, and f-score, outperforming existing approaches.

Owusu et al.[16] This study introduces a dynamic load balancing approach for SDNs using a Transformer-based Deep Q-Network (DQN). Traditional load balancing methods like Round Robin (RR) and Weighted Round Robin (WRR) are static and inefficient under fluctuating traffic conditions. Leveraging SDN’s centralized control, the proposed model combines Temporal Fusion Transformer (TFT) for traffic prediction with DQN for real-time load balancing, optimizing throughput, minimizing latency, and reducing packet loss. Simulation results show that for a 500MB data rate, the DQN model achieved 0.275 throughput, outperforming RR (0.202) and WRR (0.205), while also reducing latency and packet loss. In the 1000MB scenario, DQN outperformed traditional methods across all metrics, demonstrating its effectiveness in dynamic load management. This approach marks a step toward more adaptive and intelligent SDN management using machine learning.

Marszałek[17] et al. the growth of IT systems demands efficient communication methods for applications like streaming, cloud solutions, and Industry 4.0. Enhancing QoS, focusing on bandwidth and delay, is essential. While Active Queue Management (AQM) techniques are used, advancements like SDN offer more efficient solutions. SDN separates the control and data planes, enabling real-time traffic shaping, centralized management, and dynamic routing to improve QoS. This paper proposes an extension to the Fluid Flow analysis model for complex networks, allowing simulation of various topologies and testing of new routing and AQM algorithms. Numerical results demonstrate the model’s advantages, facilitating exploration of novel scenarios.

Wang et al. [18] with the growth of 5G and AI, CIoT applications have surged, but increased traffic on edge networks challenges network stability and QoS. The dynamic nature of CIoT Edge Network Environments (CEEs) adds complexity. This study proposes SAG, an adaptive intelligent routing algorithm combining Soft Actor-Critic (SAC), Attention Mechanism (AM), and Graph Neural Networks (GNN) to optimize edge routing in consumer-centric environments. SAG uses GNN to capture network features, AM refines these features for QoS prioritization, and SAC with Multi-Constraint Shortest Path (MCSP) makes final routing decisions. Simulation results show SAG outperforms existing algorithms, improving delay, packet loss, and throughput, while effectively meeting diverse QoS needs and demonstrating robust adaptability in dynamic environments.

Ahmed et al. [19] VANETs face challenges in accurate data transfer due to high-speed nodes and network dynamics, making routing a critical issue. This paper proposes an Optimal Geographic Cluster-based Scheduled Routing (OGCSR) protocol, consisting of three stages: multi-hop cluster formation using an Improved Chaotic Ant Swarm optimization method, cluster head selection based on optimal cluster membership, and Adaptive Neighbour Search for reducing transmission delays. OGCSR is compared with other protocols like Cluster Based Life Time Routing, AODV, and Cluster Based Directional Routing Protocol. Simulation results show that OGCSR improves packet delivery rate by 13.1%, reduces delay by 3.5%, and provides better throughput in high-density networks at a constant speed of 40 km/h.

Tan et al. [20] SDN enhances flexibility and traffic management by separating the control plane from the data plane. However, full migration to SDN is costly and complex for many organizations. Hybrid SDN offers a gradual transition, but existing strategies often focus on individual issues like traffic patterns and legacy service compatibility. This paper introduces SMART (SDN Migration Assisted by Deep Reinforcement Learning), a framework that simultaneously addresses dynamic traffic, legacy compatibility, and phased migration under budget constraints. SMART uses a DRL model combined with clustering to optimize the migration sequence, minimizing link utilization and the number of SDN-enabled nodes. Evaluation on the Abilene and GEANT network topologies shows that SMART outperforms existing approaches, achieving significant SDN benefits while migrating only 36-52% of legacy nodes, reducing costs by up to 64%. This approach provides a foundation for future research and practical guidance for cost-effective SDN migration.

Nidhya et al. [21] This study develops an intelligent system to enhance security and maintain high QoS in multi-cloud environments. Existing methods struggle with consistent security and service quality, especially in dynamic networks. To address these challenges, the study introduces an Integrated Ant Lion Optimized Boosted Gated Recurrent Unit (IANO-BGRU) for traffic analysis and malicious traffic detection. This novel approach integrates ant-lion optimization with a boosted gated recurrent unit to improve the precision of hostile traffic detection and QoS management. The IANO-BGRU method achieves 98% accuracy, 97% sensitivity, and 96% specificity in detecting malicious traffic, with a maximum processing velocity of 0.55 Gbit/s. It maintains QoS with only 2.4% active and 25% passive violations during attacks. The IANO-BGRU significantly enhances cybersecurity and QoS management, setting new benchmarks for intelligent security systems in cloud-based environments.

Encinas-Alonso et al.[22] Network slicing enables operators to offer virtual networks over a single physical infrastructure, but implementing network slices that handle traffic bursts while meeting QoS requirements has received limited attention. This paper introduces a fine-grained resource control mechanism for transport network slices, ensuring traffic QoS while managing traffic bursts and enabling efficient bandwidth sharing within and across slices. The mechanism, executed at the network’s edge, aligns with current standards on network slicing and has been tested on an experimental platform. Extensive tests show that the proposal effectively controls traffic bursts and maximizes bandwidth utilization across the network.

Kannan et al. [23] Data production has surged in recent years, with massive amounts generated from sources like social media, smartphones, and health records. WSN, which monitor and sense data, have evolved into Wireless Multimedia Sensing Networks (WMSN) to address multimedia transmission challenges, such as video, audio, and visual content. However, each node in a WMSN has energy limitations, and power consumption increases with multimedia data transmission. Key factors for efficient operation include bandwidth, packet transmission ratio, throughput, delay, jitter, frame loss, and computation time—collectively defining the network's QoS. To extend the lifetime of multimedia networks, this study proposes a novel approach that integrates Machine Learning techniques to optimize the network's functional structure.

Shukla et al.[24] The rapid growth of 5G networks and increasing User Equipment (UEs) require innovative energy efficiency solutions. UE-to-UE communication is a promising method to reduce reliance on macro cells. This paper introduces the Dynamic Resource Optimisation - Green Communication Protocol (DRO-GCP), which uses Fuzzy Logic (FL) to optimize energy-efficient UE-to-UE routing in 5G. DRO-GCP includes network deployment, route optimization, and Device-to-Device (D2D) transmission, using type-2 FL to evaluate parameters like UE speed, energy consumption, and bandwidth. The protocol selects optimal relays for data transfer, minimizing network overhead and CO2 emissions. Simulations show that DRO-GCP improves energy efficiency by 2.3-10.6% over existing methods, enhancing throughput, delay, and packet data ratio, making it a promising solution for energy-efficient 5G D2D communication.

Sheshadri et al.[25] Cloud data centers must adapt to dynamic workloads, and Network Function Virtualization (NFV) using SDNs brings programmability to networks. NFVs enable customizable network services on commodity cloud clusters, supporting multi-tenant needs. However, challenges remain in scaling to meet changing demands and improving resource efficiency. Existing solutions face issues with deployment difficulties, adaptability, and workload dynamics. This paper proposes a Hybrid Serverless Platform (HSP), combining persistent IaaS and FaaS components. The IaaS handles steady load, while FaaS activates during scaling changes to minimize service loss. The HSP controller uses QoS rules and flow statistics to make provisioning decisions, alleviating users from sizing decisions. HSP optimizes data locality, reducing transfer times between Virtual Network Functions (VNFs), and offers greater control over Service Function Chain (SFC) deployment. A proof-of-concept is provided and evaluated.

Chen et al.[26] With the growing demand for Web services, users prioritize Quality-of-Service (QoS) information when selecting services with similar functionalities. Predicting QoS values accurately remains a challenge, as traditional methods often overlook user biases and anomalous QoS data. This paper introduces HyLoReF-us, a new framework for QoS prediction. HyLoReF-us uses user reputation to assess user trustworthiness and service reputation to measure the stability of Web services. The framework employs a Logit model to calculate these reputations, and combines them with location information in an enhanced Matrix Factorization (MF) model to predict QoS values. Experiments on the standard WS-DREAM dataset demonstrate that HyLoReF-us outperforms current state-of-the-art methods, achieving better results across Matrix Densities (MD) from 5% to 30%.

Tabagchi Milan et al. [27] addresses the issue of energy waste and high carbon dioxide emissions caused by computing servers and personal devices. It proposes a task scheduling technique in green computing, focusing on load balancing in virtual machines to improve energy efficiency and reduce pollution. The approach is based on the behavioural structure of artificial bees, where tasks from overloaded virtual machines are migrated to underloaded ones, improving the QoS while reducing energy consumption. The method uses honey bees as models to migrate low-priority tasks, optimizing the system's performance. CloudSim simulations show that this technique outperforms existing methods in terms of QoS**,** makespan, and energy usage**.**

Pandey et al.[28] focuses on efficiency computation in IoT applications, specifically addressing resource management in interconnected networks. The study emphasizes key performance metrics such as availability**,** functional correctness, and throughput**,** all of which are critical for evaluating packet transfer performance. The main objective is to establish the efficiency of an IoT application using a fuzzy-based Bayesian Belief Network (BBN) model, which integrates these metrics. The Fuzzy Inference System (FIS) is used to calculate efficiency, enabling accurate computation when the metrics (availability, functional correctness, and throughput) are provided as crisp values. This approach ensures efficient resource management by leveraging the interrelation between packet transfer rates and the IoT system's overall performance.

Wang et al.[29] addresses the challenges posed by the rapid growth of CIoT applications and the increasing strain on edge networks due to surging traffic and network instability. To tackle these issues, the study introduces SAG, an adaptive intelligent routing algorithm that combines Soft Actor-Critic (SAC)**,** Attention Mechanism (AM), and Graph Neural Networks (GNN) for efficient edge routing in consumer-centric environments. SAG utilizes GNN to dynamically capture network topological features and node states, adapting to evolving consumer demands. The AM refines these features by prioritizing critical QoS parameters, ensuring tailored QoS for various CIoT applications. Finally, SAC with Multi-Constraint Shortest Path (MCSP) makes final routing decisions, optimizing QoS. Simulation results show that SAG outperforms existing algorithms, improving delay**,** packet loss, and throughput, while effectively meeting diverse QoS requirements in dynamic environments.

Sheshadri et al. [30] proposes a Hybrid Serverless Platform (HSP) to address challenges in adapting Cloud Data Centres to dynamic workloads. The platform combines Infrastructure as a Service (IaaS) for steady loads and Function-as-a-Service (FaaS) for scaling, minimizing service loss and improving resource efficiency. The HSP controller uses **QoS** rules to optimize provisioning and data locality in Service Function Chains (SFCs). A proof-of-concept evaluation showed 35% resource savings and 55% faster end-to-end times compared to traditional IaaS and FaaS implementations.

Bhardwaj et al.[31] addresses the growing security concerns in CPS, particularly in sectors like manufacturing, healthcare, and logistics, where robotic platforms and protocols are widely used. The rise in sophisticated cyberattacks on industrial robotic systems, fueled by IoT and interconnected networks, has highlighted the need for enhanced security measures. The research introduces a security framework based on attack trees, focusing on critical vulnerabilities in CPS rather than attempting to cover all devices. It categorizes physical devices and their integrated sensors using data from logs and a repository in a sensor index device library, establishing security-oriented indicators for CPS.

Vincent et al.[32] focuses on enhancing the security and privacy of Mobile Ad-hoc Networks (MANETs), which are vulnerable to sinkhole attacks where malicious nodes deceive the network by disrupting routing traffic. To address this, the study leverages FL to allow nodes to train models without sharing sensitive data, thus protecting privacy. Each node collects local routing information and contributes to a global model, which captures network behavior while maintaining privacy. The Hierarchical Deep Belief Network Convolutional Neural Network (HDBNCNN) algorithm analyzes the collected data to detect sinkhole activities by learning routing patterns. Additionally, the model can mitigate attacks by redirecting traffic and updating routing tables. The proposed approach enhances the reliability and efficiency of MANETs during attacks, reduces overhead, and strengthens flexibility against malicious traffic, providing secure communication and scalable results through performance evaluation.

Vishwanathrao et al. [33] Examines recent advancements in MANETs, emphasizing innovations like the DRLER protocol and the Trust-based Secure Routing Protocol (TSRP). These protocols optimize energy consumption and enhance network reliability, contributing to extended network lifetime and improved scalability under dynamic conditions. Despite these advances, challenges such as high computational overhead, node mobility, and limited scalability remain. The review also discusses the integration of MANETs with IoT systems, facilitating applications like livestock monitoring, and highlights the adoption of AI techniques for better routing efficiency and energy management in real-world scenarios. The paper suggests future research directions to tackle these challenges and further enhance the efficiency and reliability of MANETs.

Table 1: Related Work on Routing Path Approaches in SDN Environments

Author Ref.	Concept	Methods	Advantages	Disadvantages
S. M. Shovan et al.[34]	DynaMOSP is a parallel heuristic for Dynamic Multi-Objective Shortest Path problems, ensuring Pareto optimality with a fast parallel SOSP update and achieving major speedups on real-world graphs.	• Develop parallel algorithms for efficiently updating SOSP in dynamic networks and extend them to DynaMOSP for multi-objective optimization with CPU and GPU implementations.	• DynaMOSP achieves efficient dynamic updates, guarantees Pareto optimality, and delivers significant speedups over state-of-the-art methods on large real-world graphs.	• DynaMOSP may face scalability challenges with extremely high-frequency network changes and increased complexity .
Chunxue Xu et al.[35]	• Adaptive migration and dynamic routing models using NFV and the Multi-Armed Bandit algorithm optimize network performance by reducing costs, balancing resources, lowering delays, and maximizing efficiency.	• The study presents a dynamic migration model using network function virtualization and a Multi-Armed Bandit-based routing model with a greedy search approach to minimize migration costs, resource occupancy, and ensure safe path rates under varying node conditions.	• The proposed models enhance server resource utilization, reduce migration costs, and stabilize link load growth. They also significantly lower delays compared to traditional algorithms, ensuring improved network efficiency and reliability.	• The models may face higher initial setup complexity and require significant computational resources for real-time adaptation. Their performance may also be impacted by extreme path failure rates or highly dynamic network conditions, potentially affecting efficiency.
Hai-Anh Tran et al.[36]	GAMR, an enhanced NSGA-II for dynamic multi-objective QoS routing, improves decision speed, reduces delay and packet loss, and surpasses existing methods on Hypervolume and Inverted Generational Distance.	• The paper introduces GAMR, an enhanced NSGA-II algorithm with innovative initialization and crossover strategies for dynamic multi-objective QoS routing. Implemented in an SDN controller, it outperforms existing algorithms in key metrics such as Hypervolume, Inverted Generational Distance, forwarding delay, and packet loss.	• GAMR enhances efficiency and performance in dynamic network environments through innovative strategies, outperforms existing algorithms in key metrics, and is scalable and adaptable in SDN implementations.	• GAMR's novel initialization and crossover techniques add implementation complexity and require careful tuning, with performance improvements potentially varying across network configurations and routing scenarios.
Jian Ma et al. [37]	• This study introduces a dynamic routing method based on Q-learning to adaptively adjust routing decisions according to real-time network conditions. Simulation results show that the proposed approach increases network throughput by 30%, reduces delay by 25%, and significantly improves overall traffic optimization.	• The proposed dynamic routing method uses Q-learning to adaptively adjust routing decisions, improving network throughput, reducing delay, and enhancing resource utilization.	• The advantages of the proposed dynamic routing method include improved network throughput by 30%, reduced delay by 25%, and better load balancing, leading to more efficient utilization of network resources.	• It requires significant computational resources for continuous learning and adaptation. Additionally, the method's performance may be affected by the complexity and scale of the network environment.
Sumayah A. et al.[38]	• The Energy-Efficient Path Selection (EEPS) algorithm improves communication in the Internet of Battlefield Things (IoBT) by reducing energy consumption through smart path selection. Simulations show it	• The EEPS algorithm uses SDN to dynamically select energy-efficient paths, optimizing battery use in IoBT networks. It also incorporates a dynamic swarm head selection to ensure	• EEPS improves energy efficiency and network longevity by optimizing path selection and dynamically adjusting the swarm head for continuous communication.	• One potential disadvantage of EEPS is its reliance on dynamic swarm head selection, which may introduce complexity and overhead in network management and coordination.

	significantly extends network lifespan and cuts energy use, making military operations more sustainable.	continuous communication and enhance network longevity.		
Yu-Fang Chen et al. [39]	This work presents Lagrangian relaxation-based algorithms for optimizing resource allocation and dynamic priority assignment in SDN, improving performance and enabling effective QoS management.	The methods involve LR-based algorithms for resource optimization, dynamic priority assignment using OpenFlow, and validation through computational experiments.	the proposed approach include reduced network delay, enhanced performance under strict delay constraints, improved QoS management, and adaptability for future 6G networks.	the complexity of implementing Lagrangian relaxation-based algorithms in large-scale networks and the need for integration with AI technologies, which may require additional computational resources.
Gaby Abou Haidar et al.[40]	This work compares traditional networking and SDN, showing SDN achieves higher bandwidth and no packet loss, improving efficiency and scalability.	traditional networks (Cisco Packet Tracer) and SDN (Mininet with ODL) were simulated under varying traffic with different PC setups to compare performance.	SDN showed zero packet loss, up to 94.478% bandwidth utilization, lower latency, and better scalability compared to traditional networks.	Traditional networks had up to 5% packet loss, low bandwidth utilization (~2.443%), and increased latency with more devices.
Dourahamane IDE BARKIRE et al.[41]	This work explores how SDN can replace traditional networks to enhance QoS management using protocols like OpenFlow, iPerf, and Open vSwitch, with a focus on the QoSFlow solution for better flow prioritization and performance.	The method involves configuring SDN components using OpenFlow, iPerf, and Open vSwitch, and testing the QoSFlow solution to optimize flow prioritization and network performance.	Improved network flexibility, efficient QoS management, dynamic flow prioritization, and enhanced overall network performance through SDN protocols and the QoSFlow solution.	The implementation complexity, protocol dependence, management overhead, and scalability issues in large networks.
Shavan Askar et al. [42]	The study explores how SDN's centralized control enables the application of machine learning for efficient network management, including traffic classification, QoS prediction, and security optimization.	The method consists of a literature review to examine the integration of machine learning in SDN for traffic classification, QoS prediction, routing, and security optimization.	The enhanced network efficiency, optimized resource management, and improved traffic prediction, QoS, QoE, and security through machine learning in SDN.	the increased complexity, scalability issues, high computational demands, and challenges in implementing machine learning in dynamic networks.
Maria Daniela Tache et al. [43]	SDN centralizes network control for greater efficiency and agility while needing integration with traditional systems and solutions for scalability and resilience.	The method involves reviewing and comparing SDN optimization techniques, focusing on algorithms for routing, load balancing, and performance enhancement in large-scale systems.	The advantages of SDN include centralized control, programmability, enhanced agility, improved network management, and the ability to optimize routing, load balancing, and traffic flow in real-time.	The disadvantages of SDN include potential scalability issues, reliance on centralized control leading to single points of failure, and challenges in ensuring real-time performance, redundancy, and security.
Junyan Chen et al.[44]	The AVRO algorithm enhances SDN routing by improving convergence and avoiding local optima, outperforming deep reinforcement learning by 16.9% and traditional schemes by 71.8%.	AVRO optimizes SDN routing by enhancing AVOA's initialization and convergence phases, improving network topology awareness and outperforming baseline algorithms.	AVRO offers improved network topology awareness, faster convergence, and better global optimization, outperforming deep reinforcement learning and traditional routing schemes.	AVRO may require more computational resources for population initialization and optimization phases, and its performance could be sensitive to network complexity and topology variations.
Jiawei Xu et al.[45]	GN-DQN is a graph reinforcement learning-based SDN routing scheme that optimizes long-term revenue by leveraging graph neural networks and Deep Q-Networks for robust, optimal path selection across diverse topologies.	The method uses a GNN for network representation and DQN for optimal SDN routing path selection to maximize long-term revenue.	The advantage of this method is its ability to optimize long-term revenue by accurately selecting routing paths, generalizing to unseen topologies, and maintaining robustness to link failures.	A disadvantage is that the method may struggle with scalability in very large networks due to the complexity of training and the need for extensive data to generalize effectively.
Piotr Boryło et al.[46]	The proposed system optimizes Software Defined Networking by proactively managing flow paths, reducing packet loss, latency, and energy consumption while improving service quality and operational efficiency.	The method utilizes a modular system for proactive flow management and periodic re-optimization of routing policies, validated through real-life traffic models across various network topologies.	reduced packet loss, lower latency, improved service quality, and decreased energy consumption, enhancing overall network efficiency.	The potential complexity in system deployment, the need for continuous monitoring, and challenges in scalability across very large networks.
Muhammad Fendi Osman et al.[47]	The study presents a dynamic SDN and Deep Learning-based framework for real-time QoS management and efficient traffic allocation.	The method integrates SDN for centralized control and Deep Learning for real-time QoS management and traffic optimization.	improved network performance, dynamic QoS adjustments, real-time traffic optimization, and reduced manual intervention for sensitive applications.	the complexity of integration, potential high computational overhead from Deep Learning algorithms, and reliance on centralized SDN control, which may create a single point of failure.

Table 2: Related works on QoS in Software-Defined Networking

Author Ref.	**Concept**	**Methods**	**Advantages**	**Disadvantages**
Rasoul Farahi et al.[48]	SDN, with its separation of control and data planes, enables enhanced traffic management, but faces	The method analyses SDN architecture, classifies AI-driven load-balancing strategies,	Advantages include improved traffic management, optimized resource utilization, enhanced performance	Disadvantages include increased complexity in implementation, dependency on

	challenges like load imbalance, which AI-driven load-balancing strategies aim to address for improved performance and resource utilization.	evaluates their effectiveness, and explores emerging trends and challenges for future research.	through AI-driven solutions, and the ability to address load imbalance in SDN networks.	specific network configurations, potential scalability issues
Rehab H. Serag et al.[49]	This paper combines SDN with machine learning to enhance traffic classification in dynamic networks, demonstrating that XGBoost achieved up to 99.97% accuracy across multiple models and scaling methods.	The method integrates SDN with machine learning, applying various classification models and feature scaling techniques to optimize traffic classification and evaluate performance.	The improved traffic classification accuracy, adaptability to dynamic networks, and enhanced performance through SDN and machine learning integration.	Disadvantages include increased implementation complexity, high computational demands, scalability challenges.
Jingxu Xiao et al.[50]	MPSDMN is a multi-probability sampling-based method for detecting and locating malicious switching nodes in SDN, minimizing delay and throughput loss while reducing computational costs.	The method uses multi-probability sampling to detect and locate malicious SDN nodes by assigning sampling probabilities and applying a bisection method to reduce computational costs.	The effective detection of malicious nodes, reduced computational costs, minimal forwarding delay and throughput loss, and lightweight performance overhead.	potential limitations in scalability for large networks and reliance on accurate sampling for effective detection, which may not always capture all malicious behaviour.
Yong Liu et al.[51]	ALB-TP is an adaptive load balancing method for Data Center Networks using a GRU-Attention model to predict congestion, enhancing accuracy, scalability, and performance by reducing Flow Completion Time and improving throughput.	The method uses a GRU-Attention model for dynamic congestion prediction, two-stage routing for load balancing, and a distributed control structure to enhance scalability and performance.	The improved congestion prediction accuracy, enhanced scalability, reduced Flow Completion Time, increased throughput, and better load balancing in asymmetric topologies.	The increased computational complexity, dependency on accurate congestion prediction, and potential challenges in implementation for very large-scale networks.
Lizeth Patricia Aguirre Sanchez et al.[52]	MDQ uses Deep Reinforcement Learning for multi-path routing in SDN, dynamically optimizing traffic allocation based on QoS and congestion to provide efficient, real-time, scalable solutions.	MDQ uses DRL to optimize multi-path traffic allocation based on flow characteristics, with a multi-objective function, congestion severity index, and traffic classification, operating in an RYU-Docker OpenFlow framework for enhanced performance.	MDQ improves adaptability, reduces delay by 19%-22%, handles diverse QoS needs, and offers a scalable real-time traffic management solution.	Increased complexity, high computational demands, challenges in fine-tuning for specific networks, and dependence on accurate congestion indices and flow classification.
Kun Wang et al.[53]	This system uses a deep learning hybrid model with hierarchical detection, combining switch port statistics and wavelet transform to accurately detect abnormal traffic in SDN, improving accuracy, recall, and reducing false positives.	The method combines switch port statistics for rough detection and wavelet transform with deep learning to extract multidimensional features for fine abnormal traffic detection in SDN.	The improved accuracy, faster abnormal traffic source identification, enhanced fine detection, and a significant reduction in false positives compared to traditional methods.	The increased computational complexity, higher resource demands, and potential challenges in adapting the model to dynamic network conditions.
Artem Volokyta et al.[54]	This method combines SDN technology with multi-path routing and centralized management to optimize traffic engineering, improving QoS, reducing packet loss, and minimizing rerouting delays in computer networks.	The method integrates multi-path routing with SDN and centralized management to optimize traffic flow, ensuring QoS, and reducing packet loss and rerouting delays.	improved QoS, reduced packet loss, faster traffic rerouting, enhanced network efficiency, and better scalability through SDN and multi-path routing.	Disadvantages include increased complexity, higher computational demands, potential scalability issues, and reliance on real-time network monitoring.
Inayat Ali et al.[55]	This work introduces a policy-based routing module within an SDN framework to dynamically reroute real-time media flows based on latency thresholds, significantly improving QoS by reducing delay, packet loss, jitter, and congestion.	The method uses a policy-based routing module in SDN to monitor queuing delays and dynamically reroute real-time media flows along low-latency paths when thresholds are exceeded.	Advantages include significant reduction in end-to-end delay (80%), lower packet loss (73%), improved jitter control, enhanced QoS, and reduced network congestion.	Disadvantages include added system complexity, reliance on accurate delay threshold settings, potential overhead from frequent rerouting, and dependency on SDN controller performance.
Wei Zhou et al.[56]	This work proposes AQROM, a DRL-based mechanism that dynamically optimizes QoS-aware routing in SDN, achieving faster convergence, lower latency and packet loss, and higher throughput compared to traditional methods.	The method formulates dynamic SDN routing as a Markov Decision Process and applies the AQROM algorithm, using an Asynchronous Advantage Actor-Critic approach with dynamic reward updates to optimize QoS metrics like latency, packet loss, and throughput.	faster and more stable convergence, lower packet loss and latency, higher and more stable throughput, and dynamic adaptability to different network topologies and traffic patterns.	Disadvantages include high computational complexity, long training times, dependency on reward function tuning, and challenges in scaling for large network topologies.
Piotr Boryło et al.[57]	A proactive, modular SDN system that optimizes flow paths to boost performance, lower latency, and reduce energy consumption in real-world networks.	modular SDN system that predicts traffic, optimizes routing periodically, manages flows proactively, and validates improvements to enhance network performance and efficiency.	The system reduces packet loss by up to 30%, lowers latency by up to 2.5 times, and cuts energy consumption by up to 10%, improving network efficiency and reliability.	The proposed system enhances traffic handling, reduces latency, lowers packet loss, and decreases energy consumption, leading to more efficient and reliable network operations.
Mohammed Nsaif et al.[58]	Q-PoPS is a QoS-aware, power-optimized path selection framework for software-defined data center networks that minimizes energy consumption	Q-PoPS dynamically selects power-efficient paths in software-defined data center networks while maintaining QoS, implemented using a POX controller and evaluated with Mininet.	Q-PoPS cuts data center network energy use by dynamically choosing low-power paths while ensuring real-time QoS, delivering efficient operation without sacrificing service performance.	Q-PoPS may increase path diversity and computational complexity, potentially leading to higher overhead in path selection and slower adaptation to sudden traffic changes.

	while maintaining service quality for real-time applications.			
Harris Jr, et al.[59]	This paper introduces Delayed Dynamic Timeout (DDT), a Reinforcement Learning-based approach for dynamically optimizing flow rule timeouts in OpenFlow-compliant switches, improving flow rule match rates and efficiency.	DDT leverages Reinforcement Learning to dynamically adjust flow rule timeouts based on network traffic patterns, optimizing switch flow table utilization and improving flow rule management.	DDT improves flow rule match rates, enhances switch efficiency, adapts to changing network conditions, and outperforms static timeout values, leading to more effective flow rule management in SDN environments.	DDT may introduce additional computational overhead due to the dynamic nature of Reinforcement Learning, potentially leading to slower adaptation during rapid network changes or increased resource consumption for training.
Weichao Hu et al. [60]	This paper proposes a Software-Defined Traffic Management (SDTM) architecture based on SDN, enabling centralized traffic control, digitalization of traffic elements, and improved programmability to enhance road traffic management, reduce congestion, and improve safety.	The paper designs a three-layer SDTM architecture (operation, control, and application layers), focusing on the centralized controller's design, southbound and northbound interfaces, and hierarchical structure to enable efficient traffic management and control.	The SDTM architecture offers centralized traffic control, digitalization of traffic elements, enhanced programmability, improved traffic flow management, reduced congestion, and increased road safety.	The complexity of controller deployment, potential latency issues in centralized management, and the need for high network reliability to ensure real-time traffic control.

3. Methodology

The proposed methodology aims to address the challenges in network performance management, driven by the rapid evolution of 5G and the IoT ecosystem, through the integration of Software-Defined Networking (SDN) and advanced algorithms like Machine Learning (ML), Deep Reinforcement Learning (DRL), and dynamic load balancing.

1. To design an SDN-based network architecture that separates the control and data planes, enabling centralized management with dynamic resource allocation, flexibility, and improved Quality of Service (QoS). The system will utilize ML and DRL techniques to optimize network traffic and resource distribution by predicting real-time demand patterns and reducing congestion.
2. DN integrated with routing algorithms like CoopAI-Route, utilizing multi-agent DRL systems and Distributed Global Topology (DGT) algorithms for adaptive, predictive routing that improves scalability, fault tolerance, and performance, surpassing legacy methods like BGP. Additionally, dynamic load balancing mechanisms based on ML and DRL will efficiently distribute network resources, reducing delays and optimizing throughput.
3. In IoT-driven wireless networks, SDN will manage overhead, energy efficiency, data rates, and security, optimizing traffic across IoT models (IoMobT, IoV, IoF) for load balancing and AI integration. The Controlled Service Scheduling Scheme (CS3) will enhance scheduling through regression learning, improving rates, distribution, and reducing delays. Dynamic load balancing using ML and DRL will efficiently distribute resources, optimizing throughput and minimizing delays.
4. Ensemble SDN networks, where traditional and SDN devices coexist, will be examined for their traffic engineering needs. Advanced techniques like DRL, heuristic algorithms, and Transformer-based Deep Q-Networks (DQN) will optimize flow scheduling, link utilization, and congestion management, with their performance compared to conventional methods like Round Robin (RR) and Weighted Round Robin (WRR) in fluctuating traffic conditions.
5. The research will tackle challenges in VANETs caused by high-speed mobility and dynamic topology using the Optimal Geographic Cluster-based Scheduled Routing (OGCSR) protocol, which incorporates multi-hop cluster formation, optimal cluster head selection, and Adaptive Neighbour Search. Performance metrics like packet delivery, delay, and throughput will be compared between OGCSR and traditional protocols such as Cluster Based Life Time Routing and AODV.

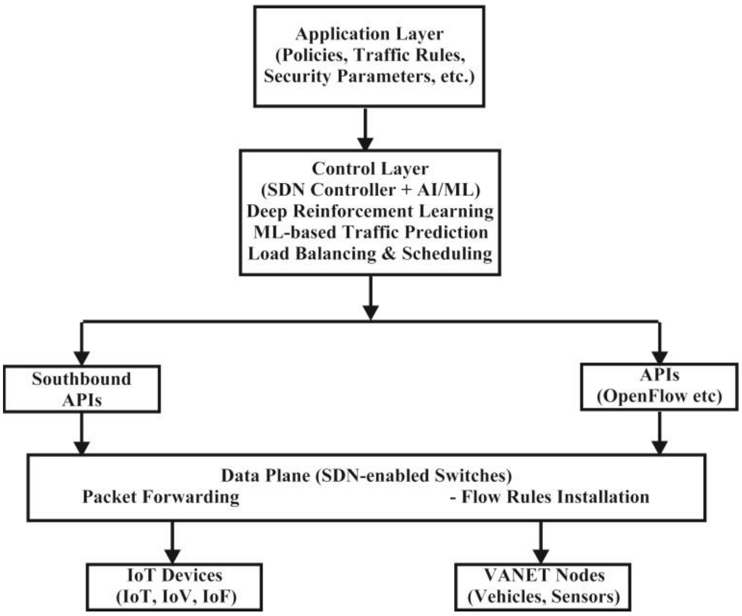

Figure 1: AI-Driven SDN Architecture for 5G-IoT Networks

4.Research GAPs

- Lack of solutions for scalability and interoperability across heterogeneous networks.
- Most current models are domain-specific and lack generalizability across diverse IoT use cases
- Limited focus on real-time threat mitigation and security frameworks under high-load conditions and dynamic topologies.
- Hybrid and intelligent models face challenges in computational complexity and energy efficiency, particularly in edge environments.
- Current models struggle to adapt to evolving network protocols and fluctuating network conditions.
- Need for lightweight, cross-layer architectures to provide scalable, secure, and energy-efficient QoS guarantees in multi-domain networks.

5. Problem Statement:

With the rapid development of 5G and IoT ecosystems, managing network performance has become increasingly complex. Traditional methods of network management are insufficient to meet the real-time demands, resource optimization, QoS requirements, and flexibility required for modern networks. The Objectives are:

1. Design and implement a scalable SDN architecture capable of dynamically allocating network resources and ensuring improved QoS across diverse and high-demand network environments.

2. To integrate AI algorithms for real-time optimization of routing, load balancing, and traffic flow management in dynamic and heterogeneous network environments.

3. To improve network reliability and efficiency by implementing predictive and adaptive routing mechanisms that proactively detect and mitigate anomalies and failures.

4. To develop AI-driven scheduling models for reducing latency and managing congestion in hybrid SDN environments

Challenges:

- Integrating SDN with legacy systems in hybrid networks while maintaining compatibility and minimizing migration costs.
- Addressing the real-time traffic demands and network overhead in IoT networks, which often involve a large number of devices with varying capabilities.
- Handling the dynamic topologies and high-speed mobility in VANETs to ensure consistent connectivity and performance.
- Ensuring security and energy efficiency in IoT-aided networks while balancing resource utilization and quality of service.
- Developing algorithms capable of scaling effectively in high-density networks, especially in vehicular and mobile IoT scenarios.

6. Conclusion

The convergence of 5G, IoT, and SDN has redefined network management, optimization, and security. This paper explored the impact of AI-driven approaches—particularly ML and DRL—in enhancing SDN-based infrastructures through improved adaptability, traffic control, and threat detection. Key models such as CoopAI-Route for intelligent routing, OGCSR for VANET performance, SMART for efficient SDN migration, and IANO-BGRU for secure cloud traffic analysis demonstrated notable improvements in packet delivery, latency reduction, scalability, and energy efficiency. These innovations highlight the potential of AI-integrated SDN to address the demands of modern, dynamic network environments. However, challenges such as legacy system integration, real-time responsiveness, and energy-aware operation persist, pointing to the need for future research in lightweight, scalable AI models and seamless hybrid network orchestration. In conclusion, the fusion of SDN, AI, and optimization strategies offers a promising foundation for intelligent, resilient, and future-ready network ecosystems.

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