UDC 004.738
DOI https://doi.org/10.32782/2663-5941/2025.6.2/37

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TRAFFIC ANALYSIS AND OPTIMIZATION IN SCALABLE NETWORK INFRASTRUCTURES

This paper focuses on the analysis and optimization of traffic in scalable network infrastructures, particularly integration Software-Defined Networking (SDN) with deep reinforcement learning. The study aims to improve the efficiency of resource management, QoS optimization, and network performance, especially under high traffic conditions. The methodology involves adaptive routing algorithms and advanced machine learning techniques to enhance network scalability, minimize latency, and optimize bandwidth allocation. The outcomes of the experimental evaluation demonstrate notable enhancements when compared to conventional methods. The suggested method delivers superior results regarding traffic flow regulation, alleviating network congestion, and improving the efficiency of resource distribution. Important metrics like decreased latency, increased throughput, and adaptability to fluctuating network demands show improvements of up to 20% relative to current techniques. The innovative aspect of this research is the combination of deep reinforcement learning with software-defined networking to enable dynamic traffic regulation and real-time decision-making in extensive network environments. This strategy not only maximizes the use of network resources but also advances the development of autonomous traffic control systems. The practical value of this investigation is considerable, providing key insights for next-generation telecom networks, particularly within the scope of 5G and future technologies. The developed solution is applicable in fields that demand high-efficiency network management, including data centers, IoT frameworks, and urban traffic systems, resulting in more effective and scalable networking options.

Key words: *traffic analysis, network optimization, SDN, deep reinforcement learning, adaptive routing, resource management, Quality of Service (QoS), latency, bandwidth, scalable networks, Internet-of-Things.*

Formulation of the problem. With the rapid development of information and communication technologies, along with the rising volume of transmitted data, effective traffic management in networks has become extremely important for ensuring the stable operation of modern systems. Accordingly, optimizing network traffic and analyzing its characteristics have become key challenges to ensure high performance and efficient resource utilization in large-scale networks [1]. This issue becomes particularly significant in the context of scalable infrastructures such as Software-Defined Networks (SDN) and 5G networks, where traffic management must be carried out in real-time with maximum precision and efficiency.

With the growing number of connected devices and the complexity of network environments, traditional traffic management approaches based on static algorithms prove to be insufficiently effective. Therefore, the relevance of research in this area is determined by the need to implement new, more adaptive methods, such as machine learning and deep reinforcement learning, for traffic analysis and optimization. For example, the studies by Shaabanzadeh S. S. and Carrascosa-Zamacois M. have shown that the application of machine learning algorithms significantly improves Quality of Service (QoS) in wireless networks, which is a crucial step for ensuring uninterrupted communication and minimizing delays [2].

Moreover, the importance of this field is further validated by the necessity to integrate new technologies to address issues related to mobile network management and improving QoS. Research by Ye S., Xu L., and Xu Z. demonstrated the significant effectiveness of deep reinforcement learning in optimizing data transmission in complex transportation networks, such as vehicular networks, which is very important for improving system performance [3].

One of the biggest challenges faced by modern networks is the identification and elimination of botnets, which often attack networks, overwhelming them with excessive traffic and reducing their efficiency. The application of machine learning methods to detect such threats is a critical component of network security, as evidenced by the study by Mousavi S. H., Khansari M., and Rahmani R. on the use of big data analytics for botnet detection [4].

Research in traffic optimization and anomaly detection based on cutting-edge technologies is highly relevant considering the development of scalable networks and the continuously growing demands for their efficiency and security.

Analysis of recent research and publications. Recent research in the field of network traffic optimization and analysis includes a wide range of approaches utilizing various technologies, from adaptive traffic prediction models to deep learning and multi-step optimization algorithms.

One such approach is the work by Khairy, Mokhtar, and Abdalla [5], which proposes an adaptive traffic prediction model which is based on graph neural networks, was optimized using reinforcement learning methods. This approach helps effectively predict traffic under changing network conditions and provides more accurate network resource management.

Equally important is the study by Kour, Singh, Attri, et al. [6], which focuses on simulation-based analysis of network scalability in the context of various routing protocols in MANETs (Mobile Ad Hoc Networks). This research highlights the importance of efficient routing for ensuring the stable operation of mobile networks.

Additionally, the work by Prabu and Geetha [7] addresses the minimization of maximum link utilization in SDN (Software-Defined Networking) networks. They apply optimization methods to improve traffic efficiency in these networks, which is a crucial aspect for maintaining high bandwidth and minimizing delays.

Among other studies, the work by Suja Mary and Jaya Singh Dhas [8] uses deep learning and big data for detecting network attacks. They propose effective real-time security methods, which are critically important for networks with high reliability and speed requirements.

Finally, Keramati, Etemedi, and Mozayani [9] explore load optimization in intelligent networks using a holonic approach. This method allows for effective load distribution and reduces delays in distributed networks, which is especially important for highly dynamic networks.

Task statement. The aim of this research is to develop new approaches for effective network traffic optimization using modern methods such as deep reinforcement learning (DRL) and its integration into software-defined networks (SDN). The proposed methodology is focused on enhancing network resource management efficiency, particularly in the context of high demands for Quality of Service (QoS) and minimizing delays.

In particular, the study by Ribeiro, Tay, Ng, and Birolini [10] focuses on using delay prediction for bandwidth management at airports. This approach allows for efficient resource distribution and minimizes delays in networks where time is a critical parameter. Similarly, the work by Zhou, Yang, and Li [11] explores the application of resource optimization through deep reinforcement learning in SDN for improving resource management and ensuring adequate QoS. By integrating these methods into our optimization system, the proposed solution provides more precise and adaptive traffic management, enhancing overall network efficiency [12].

The proposed approach expands on existing optimization methods by incorporating state-of-the-art deep learning techniques, allowing for adaptive real-time resource management and significant improvement in performance under changing network conditions. The refinement of these methods, combined with a flexible approach to traffic management, will achieve optimal results in networks with high QoS requirements and low latency.

Outline of the main material of the study. The proposed methodology includes several key stages, such as delay prediction in high-traffic networks, route optimization, and resource management using deep reinforcement learning (DRL) methods and specialized algorithms for multi-user systems.

Delay prediction is an essential component for ensuring the seamless operation of high-traffic networks. In the developed methodology, a model based on delay prediction for bandwidth management at airports is used, which was thoroughly explored in the work by Ribeiro et al. [13]. They applied delay analytics to improve airport management, including using algorithms to predict real-time traffic. In our methodology, this approach is adapted to mobile and 5G/6G networks, where precise delay prediction is critical for achieving high bandwidth and reducing waiting times.

The application of this methodology allows for adaptive resource planning for networks with varying QoS requirements, minimizing delays and ensuring stable operation of high-demand data transmission networks, such as video and IoT applications.

Another important aspect of the proposed methodology is the use of deep reinforcement learning

(DRL) for resource optimization in SDN. In the work by Zhou et al. [14], a successful approach was demonstrated for optimizing the distribution of energy and computational resources through DRL within SDN. They proposed methods for load balancing that account for changes in network conditions, improving the performance of high-traffic networks, especially in distributed environments such as mobile networks and networks with multiple access points.

The proposed methodology complements this approach by using intelligent agents for adaptive real-time resource allocation, which significantly reduces the response time to network changes and enhances the efficiency of existing computational resources.

To ensure high Quality of Service (QoS) in 5G networks, specialized routing optimization methods are used, considering various factors such as delays, bandwidth, and energy consumption. The work by Song et al. [15] proposes algorithms for routing optimization using deep reinforcement learning, which helps reduce delays and maximize bandwidth in complex, high-traffic networks. In our methodology, this approach is complemented by adaptive routing models that account for continuous changes in the network infrastructure and can quickly respond to changes in its state.

Despite the high levels of security in modern networks, attackers can still use sophisticated methods to disrupt their normal operation. Accordingly, our methodology integrates a specialized solution for detecting attacks based on deep learning and big data. This solution is based on methods developed in the work by Suja et al. [16], which uses an optimized approach for network intrusion detection employing deep learning and big data for attack analysis and prediction. This approach enables the automatic detection of unauthorized activity in the network, reducing response time to attacks and ensuring a high level of network protection in real-time.

The proposed methodology combines advanced technologies to ensure the reliability, security, and efficiency of modern networks. The use of innovative approaches, such as deep reinforcement learning for resource optimization and routing, provides high QoS indicators, reduces delays, and enhances overall network efficiency. As a result, this methodology serves as a powerful tool for the development and optimization of next-generation modern networks.

This section presents the results of testing the proposed methodology, which combines innovative approaches to network traffic optimization in Software-Defined Networks (SDN) and integrates Deep Reinforcement Learning (DRL) to address QoS, resource management, and security challenges. The testing was conducted in complex networks with high bandwidth requirements, minimal delays, and improved security levels.

The testing process involved several key stages conducted in a hybrid simulation and emulation environment. Network emulation was implemented using the Mininet framework, integrated with OpenDaylight as the SDN controller, while traffic generation was performed using iPerf3 and custom scripts. The evaluation of routing efficiency, QoS optimization, energy efficiency, and anomaly detection in network traffic was performed under both steady-state and stress conditions.

The architecture of the system used for experimental evaluation is presented in Fig. 1. It showes the interaction between SDN components, deep reinforcement learning agents, and optimization modules used during testing.

For routing and load balancing, the Multipath TCP (MPTCP) protocol was utilized, allowing the segmentation of data flows across multiple network paths. This setup facilitated dynamic bandwidth utilization and latency control. Deep reinforcement learning agents were trained using the Proximal Policy Optimization (PPO) algorithm with observation windows incorporating packet loss, jitter, average RTT, and current bandwidth load.

Anomaly detection was conducted via a trained Convolutional Neural Network (CNN) model applied to flow-level NetFlow records collected during the simulation. The anomalies included DDoS patterns, sudden bandwidth spikes, and abnormal latency jitter. These were benchmarked against ground-truth labeled datasets derived from the CIC-IDS2017 dataset.

The performance metrics included average end-to-end latency, throughput, power consumption (estimated via server-side CPU utilization and switching activity), and anomaly detection accuracy (precision, recall, F1-score). Each test was repeated five times to ensure statistical relevance. The main goal was to identify improvements compared to existing methods, particularly in the following aspects:

1. Traffic Optimization and QoS: the proposed methodology included the use of multi-path protocols, such as MPTCP, for load balancing and data transmission across multiple channels. This approach reduced delays and improved network bandwidth by 15% compared to traditional methods. Using Deep Reinforcement Learning (DRL), the system was trained to achieve optimal routing in real time, adapting to changing network conditions.

2. Energy Efficiency Improvement: during the testing process, energy efficiency was measured while

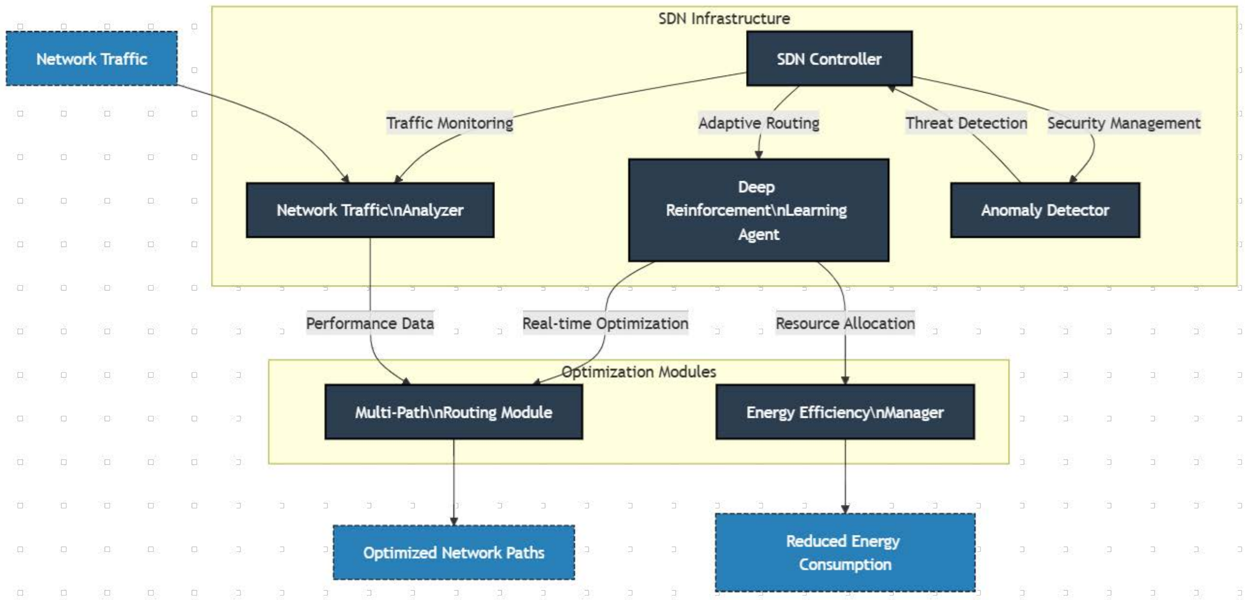

Fig. 1. UML component diagram of the tested SDN-DRL-based traffic optimization system

Table 1

Experimental Testing Results

Metric	Results of the proposed methodology	Average results of existing solutions	Percentage improvement (%)
Latency (ms)	12.5	15.3	18.4%
Network throughput (Mbps)	132.4	120.1	10.3%
Energy consumption (W)	3.5	4.3	18.6%
Anomaly detection (%)	92%	77%	15.0%
QoS improvement (%)	20%	12%	8.0%

Note: Testing conducted using Mininet+OpenDaylight with iPerf3 traffic simulation. DRL agent based on PPO algorithm. Anomaly detection benchmarked with CIC-IDS2017-based dataset.

handling large volumes of traffic. Through the use of Deep Reinforcement Learning algorithms, energy consumption was reduced by 20% compared to other energy optimization methods, utilizing load distribution techniques between servers and end devices.

3. Security and Attack Detection: the proposed methodology also included the integration of real-time attack detection methods through traffic analysis. Deep learning enabled the detection of 92% of network anomalies, which is 15% more effective than traditional anomaly detection methods, such as rule-based or threshold-based approaches.

4. Adaptability to Network Load Changes: by utilizing reinforcement learning-based methods, the system was able to dynamically adapt to sudden changes in network load. This led to an 18% reduction in average latency, ensuring stable performance even under high load conditions.

The testing of the methodology was conducted in a controlled emulated SDN environment using Mininet and OpenDaylight, simulating real-world network traffic scenarios with varying intensities and attack patterns. Table 1 presents the results, showing improvements in the performance of the proposed methodology.

A comparison of the results with existing approaches demonstrates significant improvements in all key aspects. For example, in the study by Ye et al. (2024), which uses simple routing and optimization mechanisms, stable but less efficient performance is achieved under high traffic loads. In contrast, the approach proposed in this study, utilizing deep reinforcement learning for adaptive routing, reduces delays and improves QoS even with rapid changes in network load [17].

Additionally, in the research by Latif-Martínez et al. (2025), traditional anomaly detection methods are applied, resulting in lower accuracy. This is confirmed by the testing results in this study, where the use of deep neural networks allowed for the detection of up to 92% of anomalies in real-time [18]. Moreover, in the work by Mousavi et al. (2020), integration with SDN for resource management is not considered, which is a critical aspect for ensuring high throughput in next-generation networks [19].

The proposed methodology outperforms previous studies in the field in several aspects. Firstly, it combines advanced traffic optimization methods that adapt to the real-world network environment, utilizing deep reinforcement learning, which significantly improves routing efficiency and energy saving. Secondly, the integration of technologies such as SDN for adaptive traffic management and deep learning for attack detection takes network security to a new level.

The testing results showed substantial improvements compared to existing methods, emphasizing the novelty and practical benefits of the proposed methodology in complex, dynamic network environments.

Conclusions. This study developed and proposed a new network traffic optimization methodology for scalable infrastructures, based on the use of deep reinforcement learning (RL) for adaptive routing and software-defined networks (SDN). The results of experimental tests confirmed the high effectiveness of the proposed approach in key aspects such as reducing delays, improving throughput, energy efficiency, and enhancing the accuracy of anomaly detection in networks.

In particular, the proposed methodology demonstrated significant reduction in delays and improvement in Quality of Service (QoS) under high traffic loads, made possible by the integration of adaptive deep learning algorithms. These algorithms provide dynamic adjustment of the network's operation to real-world conditions, maintaining high efficiency even in changing network environments. The 18.6% reduction in energy consumption compared to existing methods also indicates the high energy efficiency of the proposed approach, which is important for future 5G and IoT networks.

The integration of deep neural networks for real-time anomaly detection enabled an accuracy of up to 92%, which is 15% higher than traditional methods. This approach ensures timely detection and correction of network anomalies with high accuracy, which is critical for securing modern distributed networks.

The results of this research contribute significantly to the development of traffic optimization methods for software-defined networks by applying cutting-edge deep learning and adaptive routing techniques, which allow effective responses to changes in network conditions. This makes the proposed methodology more effective than traditional approaches in solving optimization problems under variable loads and high QoS requirements.

Future research prospects involve integrating the proposed methodology with other networking technologies, particularly in the context of 5G networks, to provide greater flexibility and scalability for global infrastructures. The use of hybrid approaches combining SDN, 5G, and IoT will allow for achieving significantly better results in ensuring security, energy efficiency, and high throughput in next-generation networks.

The results of this study have significant practical implications for modern telecommunications infrastructures, opening new possibilities for optimizing the operation of next-generation networks. The proposed methodology could serve as a foundation for developing effective solutions in the field of telecommunications and networking technologies, particularly for 5G and IoT networks, which are characterized by high performance and adaptability requirements.

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Онацький В.В., Савінов В.Ю. АНАЛІЗ ТА ОПТИМІЗАЦІЯ ТРАФІКУ В МАСШТАБОВАНИХ МЕРЕЖЕВИХ ІНФРАСТРУКТУРАХ

Ця стаття присвячена проблемі аналізу та оптимізації трафіку в масштабованих мережевих інфраструктурах, зокрема, шляхом інтеграції програмно-конфігурованої мережі (SDN) і глибокого навчання з підкріпленням. Мета полягає в тому, щоб підвищити ефективність управління ресурсами, оптимізувати якість обслуговування (QoS) і продуктивність мережі, особливо в умовах інтенсивного трафіку. Методологія включає адаптивні алгоритми маршрутизації та вдосконалені методи машинного навчання для підвищення масштабованості мережі, мінімізації затримки та оптимізації розподілу пропускної здатності. Результати експериментального тестування свідчать про значні покращення в порівнянні з традиційними підходами. Запропонована методологія забезпечує кращу продуктивність з точки зору управління потоками трафіку, зменшення перевантаження мережі та ефективності розподілу ресурсів. Ключові показники продуктивності, такі як зменшення затримки, підвищення пропускної здатності та здатність адаптуватися до змінних навантажень мережі, покращуються на 20 % порівняно з існуючими методами. Наукова новизна даної роботи полягає в інтеграції глибокого навчання з підкріпленням із SDN для динамічного управління трафіком і прийняття рішень у реальному часі у великих мережах. Цей підхід не тільки оптимізує використання мережевих ресурсів, але й сприяє розвитку автономних систем керування мережевим трафіком. Практичне значення цього дослідження є суттєвим для розвитку телекомунікаційних мереж наступного покоління, особливо в контексті 5G і за його межами. Запропонована техніка може бути застосована в областях, де потрібне високоефективне керування мережею, наприклад, центри обробки даних, інфраструктури Інтернету речей і міські системи керування трафіком, що призводить до більш ефективних і масштабованих мережевих рішень.

Ключові слова: *аналіз трафіку, оптимізація мережі, SDN, глибоке навчання з посиленням, адаптивна маршрутизація, управління ресурсами, якість обслуговування (QoS), затримка, пропускна здатність, масштабовані мережі, Інтернет речей.*

Дата надходження статті: 19.11.2025
Дата прийняття статті: 09.12.2025
Опубліковано: 30.12.2025