

Comparative analysis of load balancing methods based on SDN/NFV

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Abstract. The purpose of the study was to determine the advantages and disadvantages of using load balancing methods in networks based on Software-Defined Networking and Network Functions Virtualisation technologies. Particular attention was paid to comparing the effectiveness of different approaches to balancing, including centralised and distributed methods, and the use of intelligent algorithms for load forecasting. The analysis helped to identify the advantages and disadvantages of each method, and their ability to adapt to changing network traffic conditions, considering such parameters as bandwidth, latency, packet loss, and energy efficiency. The paper discussed methods of load balancing in networks based on Software-Defined Networking and Network Functions Virtualisation technologies, which are important for ensuring the efficiency, scalability, and adaptability of modern networks. The key challenges faced by these technologies are described, such as the dynamism and unpredictability of traffic, resource optimisation, energy efficiency, and the integration of intelligent algorithms for load forecasting and energy consumption reduction. The study presents a comparison of various load balancing methods, including centralised and distributed traffic management, and the use of virtual balancers and adaptive traffic redirection algorithms. Particular attention was paid to analysing the impact of these methods on throughput, latency, packet loss, and energy efficiency under different traffic conditions. The role of machine learning in optimising load balancing processes, and the possibilities of integrating Software-Defined Networking and Network Functions Virtualisation into hybrid networks were considered. According to the results of the study, the use of balancing methods based on Software-Defined Networking/Network Functions Virtualisation can significantly improve network efficiency, reduce latency and increase throughput, while reducing energy consumption under high loads. Key results for Ukraine, where the integration of Software-Defined Networking/Network Functions Virtualisation into the telecommunications infrastructure can become the basis for improving the quality of services, optimising costs, and ensuring a high level of security in the context of digital transformation and infrastructure modernisation, are derived

Keywords: network functions virtualisation; intelligent algorithms; resource optimisation; hybrid structures; energy efficiency

Introduction

Modern network infrastructures, especially in large corporations and data centres, face unprecedented workload due to the growth of data volumes, the active introduction of cloud technologies and the Internet of Things (IoT). In the context of digital transformation, the issue of ensuring reliability, scalability, and efficiency of traffic management in networks is becoming particularly relevant. This is where innovative approaches such as Software-Defined Networking (SDN) and network functions based on NFV (Network Functions Virtualisation) come to the fore, offering radically new approaches to optimisation and load balancing.

Load balancing is one of the key tasks of the network infrastructure, because the efficiency of resource allocation depends not only on the quality of user service, but also on the performance of the network as a whole. Conventional approaches to load balancing are often limited by static rules, which is not always effective under variable network conditions and high traffic dynamics. Using SDN and NFV technologies to implement dynamic balancing techniques allows networks to automatically adapt to the current load, ensuring efficient resource allocation in real time. SDN technology separates network management from its

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physical infrastructure, helping to centrally monitor traffic and provide flexible load balancing based on user needs. NFV, in turn, allows migrating network functions to virtual platforms, which simplifies resource management and reduces dependence on hardware.

The problem is that different balancing methods based on SDN and NFV have their own characteristics and limitations. For example, some methods may be more effective for cloud environments, while others may be more effective for data centres or IoT infrastructure. There are also questions about reliability, scalability, security, and speed of response to changes. Thus, a comparative analysis of existing SDN/NFV-based load balancing methods is necessary to select the optimal approach that meets modern network infrastructure requirements.

The study by J. Billingsley *et al.* (2020) analysed adaptive balancing methods for cloud services, where the load often varies depending on the number of users. Researchers have found that SDN/NFV technologies significantly improve resource efficiency in cloud environments, improving performance. A. Das *et al.* (2025) considered security aspects related to load balancing, in particular, protection against DDoS attacks. Using SDN, the researchers created a system that not only distributes the load, but also identifies abnormal network activity. A.M. Zarca *et al.* (2019) analysed the effectiveness of various balancing methods for IoT networks, where the use of SDN/NFV proved useful for managing a large number of devices. They noted that NFV technology allows effectively managing different levels of device priority.

A. Filali *et al.* (2020) examined methods for predictive load balancing based on historical data. Using SDN and machine learning algorithms, they created a system that can predict peak load moments and allocate resources accordingly. Z. Song *et al.* (2019) reviewed balancing methods adapted for e-commerce systems that require high reliability and fast response to user requests. Research has shown that SDN/NFV-based methods can reduce request processing delays. M. Alenezi *et al.* (2019) focused on opportunities to reduce infrastructure costs through the use of SDN/NFV in telecommunications networks. This study proved that centralised control and virtualisation can reduce the need for physical hardware. The study by Q. Zhou *et al.* (2021) compared static and dynamic balancing methods. The researchers found that dynamic SDN-based methods distribute the load more efficiently in conditions of high traffic changes. L. Zhu *et al.* (2020) compared the impact of different protocols on SDN network performance. They found that the choice of protocol can significantly affect the speed of request processing, and in particular, OpenFlow protocols provide the highest performance. In addition, P.P. Ray & N. Kumar (2021) examined the impact of SDN/NFV on network flexibility in computing power allocation in multi-cloud environments. The results showed a significant reduction in infrastructure maintenance costs while increasing network performance.

An analysis of available studies showed that SDN/NFV-based load balancing methods have demonstrated their

effectiveness, but there are still several aspects that need to be studied in more depth. Among the unexplored or under-covered topics were the adaptability of methods to heterogeneous network environments, such as multi-cloud environments or hybrid networks; energy optimisation, which is important in the context of growing demands for green technologies; and the use of artificial intelligence and machine learning for load forecasting and dynamic resource allocation in SDN/NFV networks.

The purpose of this study was to investigate the effectiveness of various load balancing approaches using SDN/NFV technologies by benchmarking them. To achieve this goal, the following tasks were solved: to compare the efficiency of various SDN/NFV load balancing methods in multi-cloud and hybrid environments; to evaluate the energy consumption of these methods and their compliance with modern energy efficiency requirements.

Materials and Methods

An integrated approach to the study of network resource management was applied to analyse load balancing methods in networks based on SDN and NFV technologies. This made it possible to determine the efficiency, flexibility and scalability of the network infrastructure in the context of modern requirements for telecommunications systems. The study used two key approaches to load balancing: centralised management and decentralised balancing. For the first approach, the SDN controller plays a central role, which makes decisions based on global network status information. In decentralised balancing, each node makes autonomous decisions using only local data. This approach provides greater reliability in the event of a central element failure, but requires more calculations on each node.

Machine learning algorithms that can predict loads based on historical data were used for modelling and analysis. Methods for analysing traffic patterns considering peak loads were integrated, which ensured optimisation of traffic routing in dynamic and complex network environments. In particular, regression, clustering, and adaptive learning algorithms were considered, which allowed improving the accuracy of forecasts. The effectiveness of balancing methods was evaluated based on quantitative parameters such as throughput, latency, packet loss, power consumption, and adaptability under variable load conditions. These indicators were selected as the most important for evaluating the performance of the network infrastructure. To obtain the results, simulations were used with the help of tools such as Mininet for modelling SDN networks and specialised Python libraries for implementing machine learning algorithms.

Special attention was paid to energy efficiency analysis, which is an important aspect for modern data centres. A comparison of different algorithms, such as Round Robin, Least Connection, Weighted Least Connection, Shortest Queue First and Adaptive Load Balancing, helped determine which method is best suited to balancing certain types of load under different network conditions to reduce energy consumption and make optimal use of network

resources. Various scenarios were modelled in experiments, in particular peak load conditions, to assess the system's behaviour in critical situations. Reliability and security issues were also considered, as a centralised SDN controller can become system vulnerability. To reduce such risks, approaches to implementing backup management mechanisms that ensure uninterrupted network operation even in the event of a central node failure were investigated. To assess the flexibility of network solutions, special attention was paid to multi-cloud and hybrid environments that require rapid adaptation to changes in network structure and traffic. Two scenarios for using SDN/NFV in such environments were modelled to determine optimal configurations.

All experiments were carried out considering the needs of modern telecommunications systems, in particular, the need to ensure high bandwidth, low latency, and high network availability, which is becoming increasingly important due to process automation. The obtained data were analysed for such parameters of efficiency of methods as adaptability to variable traffic, power consumption, and speed of response to loads. The analysis was based on a comparison of different approaches to load balancing, including centralised and decentralised methods, considering specific infrastructure requirements and system performance in real-world operating conditions.

Results

Load balancing in SDN and NFV-based networks is a complex and multidimensional task that involves a number of technical and organisational challenges. One of the main problems is the dynamism and unpredictability of traffic, because the volume of traffic often changes due to user demand, peak loads, or specific events, such as new product releases or network attacks. This creates a significant load on the system and requires constant dynamic balancing to avoid congestion and ensure stable network operation. The second important problem is resource optimisation: load balancing in an SDN/NFV environment should consider the available resources of each network node and optimise them as much as possible, considering the different requirements of virtualised network functions (VNF), such as CPU time, memory, and bandwidth. In addition, energy efficiency is an important aspect: load balancing should help to reduce power consumption, especially for large data centres. Using SDN/NFV can help to allocate resources more efficiently, but it requires specialised algorithms to reduce energy consumption (Tipantuna & Hesselbach, 2020). There is also the question of integrating intelligent algorithms, because modern networks are extremely complex and variable, which requires intelligent approaches such as machine learning. The implementation of such algorithms faces challenges related to computing costs, training models, and ensuring real-time operation, and raising issues of data security and privacy.

Another important challenge is scalability and flexibility, especially for multi-cloud and hybrid environments that require adaptive solutions to handle large volumes

of traffic and provide a fast response to structural or load changes. In addition, reliability and security must be considered, since a centralised SDN controller increases network vulnerability and must be protected from threats that may disrupt the balancing or stable operation of network functions. Another important problem is latency and throughput: when implementing load balancing, it is necessary to minimise latency and maintain high network throughput, which is a difficult task with large volumes of traffic and interaction with different types of infrastructure (George, 2022). Integration of SDN and NFV is an important technological component of modern network systems, because both of these technologies are aimed at improving the flexibility, scalability, and efficiency of network infrastructure. When combined, SDN and NFV offer the ability to dynamically manage network resources and quickly adapt the network to changing needs, which is especially important in an era of growing traffic and performance requirements (Bonfim *et al.*, 2019).

The basic principle of integration was to use an SDN controller to manage network traffic and routing, while NFV was responsible for virtualising network functions (such as routers, firewalls, load balancers) on public hardware. SDN allows centrally managing traffic routing, movement, and prioritisation using software that provides fast network configuration (Kaur *et al.*, 2020). NFV, in turn, allows performing functions normally performed by specialised hardware on virtual machines or containers.

SDN and NFV integration provides several key benefits. Network management flexibility increases: network functions can be quickly migrated or scaled to meet traffic needs without the need for physical hardware replacement. This significantly reduces the cost of network deployment and maintenance, and allows quickly adapting to new business requests. SDN/NFV allows centrally monitoring network resources and providing efficient traffic management, which greatly simplifies load balancing and improves network performance. However, the integration of SDN and NFV is not without its challenges. Ensuring compatibility between components that may come from different manufacturers is challenging. The lack of generally accepted standards for certain aspects of SDN/NFV technologies can complicate deployment and lead to compatibility issues. The integration of these technologies increases security requirements, as a centralised SDN controller can become vulnerability in the infrastructure, creating network security risks. In addition, with the integration of SDN and NFV, the requirements for computing resources and monitoring systems are increasing. Managing and monitoring the status of virtualised functions requires high performance and reliable monitoring tools to identify and solve potential problems in real time. To reduce computing costs, artificial intelligence and machine learning technologies are being actively explored, which can optimise resource allocation and predict network loads. SDN/NFV-based load balancing methods are key components of modern network infrastructures, as they allow dynamic and efficient load

distribution between different network nodes, considering performance requirements and minimising the likelihood of delays or congestion (Nawaz *et al.*, 2024). One of the main approaches to load balancing in SDN is to centrally manage traffic through the SDN controller, which receives information about the state of the network from all its parts and optimally distributes traffic between network nodes. The controller can predict future load based on current and past trends, and based on this information, change traffic routes to avoid congestion (Lakhani & Kothari, 2020). This approach reduces latency and ensures efficient use of network resources.

Distributed load balancing is an alternative method in which traffic balancing occurs without centralised control. In this case, each network node independently determines how to distribute traffic based on local network status information. Distribution balancing uses routing and adaptive network algorithms, in particular traffic hashing, which allows evenly distributing the load between different routes without the need for a central controller, which reduces the load on the central system and increases scalability.

NFV technologies allow dynamically changing the infrastructure by virtualising network functions, such as routers or load balancers. This allows quickly scaling the network by adding or reducing the number of virtual functions depending on the current load. This approach not only improves network performance, but also significantly reduces physical hardware costs, since functions can be performed on public virtual platforms. The use of machine learning algorithms opens up new opportunities for load balancing, allowing the prediction of loads based on

historical data and optimisation of traffic routing using intelligent systems that can adapt to changes. Machine learning algorithms can analyse traffic patterns and predict peak loads, which allows performing balancing in advance and reducing the risk of network congestion.

In complex hybrid networks that use both conventional technologies and SDN, load balancing must consider both virtual and physical resources. Balancing mechanisms can integrate different routing strategies and adapt to different types of traffic, which ensures high network performance and reliability. An important part of this approach is the use of policies that optimise resource usage and minimise congestion in certain parts of the network. Thus, the use of various load balancing methods based on SDN/NFV allows ensuring high efficiency of networks, increasing their scalability, and reducing the likelihood of congestion. The choice of a particular method depends on the specifics of the network and its needs for flexibility, speed of adaptation, and efficiency of resource management.

Load balancing is a key task in modern Software-Defined Networks (SDN) and Network Functions Virtualisation (NFV). The efficiency of this process significantly affects the quality of network operation, including bandwidth, latency, packet loss, and overall power consumption. Different methods, such as centralised and decentralised management, virtual balancers, and adaptive redirection algorithms, show different performance depending on traffic characteristics and environmental conditions. Table 1 summarises the main comparison parameters, such as bandwidth, latency, packet loss, power consumption, and adaptability to load changes.

Table 1. Comparative characteristics of load balancing methods in SDN/NFV networks by key metrics

Method	Bandwidth (Gbps)	Delay (ms)	Packet loss (%)	Power consumption (W)	Flexibility for traffic changes
Least delay	8.5	15	2.5	250	Average
Adaptive redirection	9.2	12	1.8	300	High
Virtual balancer	10	10	1.2	280	High
Centralised management	7.5	20	3	200	Low
Decentralised management	8	18	2	220	Average

Source: created by the author based on N. Giri *et al.* (2018), M.F. Monir & D. Pan (2021)

The analysis showed that different load balancing methods have their advantages and disadvantages. The virtual balancer showed the best results in terms of bandwidth, minimising latency and packet loss. It was also highly adaptable to changes in network traffic, making it suitable for complex and dynamic networks. However, its power consumption has proven to be high, which can be a critical factor for some environments. Centralised and decentralised management methods have different levels of energy consumption, which is an important aspect for assessing their compliance with modern energy efficiency requirements. Centralised management, due to the centralisation of resources, can reduce energy consumption by optimising the use of equipment, although it is inferior in performance in large and distributed networks. On the

other hand, decentralised management, despite increased energy consumption, has advantages in scenarios with high resource allocation, where energy efficiency is less critical compared to flexibility and adaptability.

The lowest latency method, while showing average adaptability, also meets energy efficiency requirements in stable traffic conditions, where the need to adapt to variable loads is lower. However, for more dynamic environments where high adaptability and scalability are required, additional energy saving mechanisms may be needed, such as the use of specialised hardware platforms or algorithms optimised for energy efficiency. Thus, the choice of balancing method should consider not only performance and adaptability, but also compliance with energy efficiency requirements, which include minimising energy

consumption while maintaining the required level of efficiency for different types of network environments. The results of the study can become the basis for improving methods of balancing and further optimising energy consumption in SDN/NFV networks that meet modern energy efficiency requirements.

With the introduction of SDN and NFV technologies, it became necessary to improve load balancing methods in networks to effectively manage traffic and ensure high quality of services. The main goal of such methods is to optimally distribute the load between servers, routers, and other network components to prevent congestion and reduce delays, especially in dynamic traffic conditions. There are several different approaches to load balancing, each with its own advantages and disadvantages, depending on the specifics of the network and its performance requirements. Load distribution in SDN/NFV networks can significantly

improve the adaptability of the network, its ability to scale, and its response to changing load conditions. Since networks with SDN and NFV differ from conventional ones in that they can be configured programmatically to optimise traffic, the chosen balancing method should consider the dynamism and variability of traffic, and the resource requirements that are available in each specific situation.

Table 2 compares the main load balancing algorithms used in SDN/NFV networks, with a focus on important parameters such as response speed, real-time efficiency, scalability, and application in various environments. The table helps to assess how each algorithm behaves in a particular environment, which allows network developers and engineers to select optimal solutions for implementation in real-world conditions, which is an important stage for ensuring the smooth operation of critical network services, in particular, in the context of 5G and IoT development.

Table 2. Comparison of load balancing algorithms in SDN/NFV networks: efficiency and application in different network environments

Balancing algorithm	Network type	Load response time	Real-time efficiency	Scalability	Application
Round Robin	SDN/NFV	Moderate	Average	Low	Small and medium-sized networks
Least Connection	SDN/NFV	Fast	High	Average	Networks with uneven load
Weighted Least Connection	SDN/NFV	Fast	High	Average	Networks with different resource requirements
Shortest Queue First	SDN/NFV	Very fast	High	High	Networks with high bandwidth requirements
Adaptive Load Balancing	SDN/NFV	Very fast	Very high	Very high	Large networks, high-load environments

Source: created by the author based on S. Rout *et al.* (2020), T.G. Thajeel & A. Abdulhassan (2021)

Each of the presented algorithms has its own advantages and limitations. For example, the Round Robin algorithm is easy to implement, but its performance is limited in large or high-load networks. At the same time, Least Connection and Weighted Least Connection show better results when handling uneven loads, although they require more computing resources. The Shortest Queue First and Adaptive Load Balancing algorithms provide high real-time efficiency, making them optimal for large and dynamic networks. Since each of the methods has its own characteristics, it is important to choose an algorithm depending on the specifics of the network and its requirements. The use of these technologies allows optimising resources, reducing latency, and increasing network throughput. The use of intelligent algorithms for load forecasting also opens up new opportunities for achieving high efficiency in variable traffic conditions.

Modern information systems require not only high performance, but also reliability. The use of SDN/NFV technologies allows implementing adaptive backup mechanisms that increase fault tolerance, ensuring the continuity of services in different environments. Among the key redundancy mechanisms, there are three approaches: active-active, active-passive, and policy-based redundancy. The active-active model demonstrates the highest efficiency due to the simultaneous operation of several nodes, although it requires significant resources. Instead, the active-passive

approach saves resources, but is more vulnerable to delays in switching. Policy-oriented redundancy offers flexibility, but depends on the effectiveness of the monitoring system.

In multi-cloud environments, SDN/NFV helps to optimise resources through platform integration. For example, dynamic traffic balancing between cloud providers minimises latency and distributes the load evenly. Another aspect is the centralised implementation of security features, such as virtual firewalls, which allow protecting data in distributed clouds. In hybrid environments, these technologies play a critical role in automating resource management. Integration allows smoothly switching between on-premises and cloud resources, reducing system downtime. Additionally, the use of virtualised backup functions ensures business continuity by allowing traffic to be quickly redirected in the event of a primary infrastructure failure.

The implementation of these scenarios illustrates the potential of SDN/NFV to overcome conventional network constraints. It provides high performance, flexibility, and reliability in multi-level environments, which is an important step towards the dynamic and adaptive infrastructures of the future. Table 3 shows a summary of the key benefits and challenges of each environment. This provides a clear picture of the practical implementation of SDN/NFV in multi-cloud and hybrid scenarios, which are the basis for sustainable network infrastructures.

Table 3. Comparison of SDN/NFV usage scenarios in multi-cloud and hybrid environments

Category	Multi-cloud environment	Hybrid environment
Backup mechanisms	Load balancing between providers; optimising data routes to ensure fault tolerance	Use on-premises reserves and private clouds to ensure continuity of work
Security	Centralised monitoring; tunnelling to protect data transfer between clouds	Access control to local data; integration with private cloud security policies
Scenario 1: Scalability	Additional resources are connected in real time to handle peak load	Use of cloud infrastructure as a reserve to improve productivity during peak times
Scenario 2: Recovery	Automatically redirects traffic to an alternative provider in the event of a failure	Local storage of critical data with the ability to automatically switch to the cloud in case of failures

Source: created by the author based on M.S. Bonfim *et al.* (2019), H.U. Adoga & D.P. Pezaros (2022)

In a multi-cloud environment, the use of SDN/NFV allows creating effective strategies for traffic management and security at all infrastructure levels. SDN allows centrally managing security policies, optimising resource usage to reduce costs and improve performance. NFV allows quickly implementing new network features, reducing dependence on physical devices and increasing flexibility. For example, in the process of automating the allocation of resources between different clouds, it is possible to reduce response time and improve the ability to scale.

However, in a hybrid environment where both public and private clouds are combined, SDN/NFV provides the ability to provide more reliable connection management between different cloud platforms. Due to integration with NFV, it is possible to organise effective monitoring and management of resources to ensure stability and security in the face of constant changes. One of the main advantages of this approach is the ability to ensure continuous operation of the enterprise, even if some resources are decommissioned or transferred to another platform to perform tasks. Therefore, the integration of SDN/NFV into multi-cloud and hybrid environments allows achieving a high level of adaptability, reducing costs, and improving the management and security characteristics of the infrastructure. This is especially important for organisations that work with large amounts of data and have a complex infrastructure that requires flexibility in load distribution and business process continuity. This development towards using SDN/NFV has huge potential to save resources and improve infrastructure efficiency. These technologies allow Ukrainian telecommunication operators to introduce new services, ensure optimal use of their networks and improve the quality of service, which is especially important in the context of the growing demand for digital technologies in the country.

For Ukraine, the issue of load balancing in SDN and NFV networks is of particular relevance in the context of digital transformation and infrastructure modernisation. Given the growing demand for high-quality Internet access, the introduction of these technologies can significantly improve the efficiency of traffic management in telecommunications systems. In addition, the introduction of SDN/NFV methods allows Ukrainian telecommunication operators to optimise costs, provide greater flexibility in deploying services, and adapt to the growing needs of both the commercial and public sectors. In addition,

the development of SDN/NFV can become the basis for improving cybersecurity, which is especially important in the face of modern challenges. The participation of Ukrainian IT companies in the development of solutions based on these technologies contributes to their integration into the international innovation market. Given limited resources, the introduction of more energy-efficient traffic balancing techniques is also an important factor in reducing operating costs and maintaining environmental sustainability. Further research on the effectiveness of these methods in local conditions can become the foundation for their adaptation to the realities of Ukrainian network infrastructures.

However, these prospects require government support and a strategic approach to implementing SDN/NFV. It is important to train specialists who can develop, implement, and maintain such solutions, and ensure their compliance with cybersecurity standards. Thus, research and adaptation of SDN/NFV can contribute to a significant improvement in the network infrastructure of Ukraine, laying the foundation for further digitalisation of the economy and society.

Discussion

The study of load balancing methods in networks based on SDN and NFV technologies has shown that these approaches can significantly increase the efficiency of network management, reducing the likelihood of congestion and improving performance. A central aspect of the study was the comparison of two main methods: centralised and decentralised load balancing. The results showed that each of them has its own advantages and disadvantages, depending on the requirements for scalability, flexibility, and energy efficiency of the network.

Centralised management, where the SDN controller acts as a single decision centre, allows achieving high efficiency in conditions of stable and predictable traffic. However, in the face of rapid load changes, this method may have limitations due to the need to process large amounts of data centrally. The study by M.D. Tache *et al.* (2024) considered a centralised approach to load balancing in SDN networks using conventional routing algorithms. The results showed that centralised management is effective in networks with constant and predictable traffic, but its efficiency is significantly reduced at high load peaks. The researchers emphasise that centralised systems have

limits on the speed of response to changes in the network, which causes delays in processing requests. In this study, it was found that centralised balancing ensures stable network operation in environments with low traffic variability, but its efficiency is significantly reduced in conditions of high dynamics or under unexpected loads. F. Chahlaoui & H. Dahmouni (2020) pointed to the problem of optimising centralised load balancing in SDN networks, in particular, in the context of using conventional routing algorithms. The main objective of the study was to determine the effectiveness of the centralised approach in conditions of constant and predictable traffic, and to identify the limitations of this approach when working with high load peaks, such as traffic spikes or processing large amounts of data in real time. The researchers focused on centralised approaches under stable load, while the current study focused on flexible and adaptive algorithms that can effectively respond to variable conditions. In addition, the use of NFV and machine learning to optimise system performance under high traffic peaks was analysed.

On the other hand, decentralised load balancing, where each node of the network independently makes decisions about traffic routing, demonstrated a high level of adaptability to changes in load. In situations with extreme load or unstable traffic, this method can significantly improve response time and reduce the likelihood of congestion on specific nodes. Z. Nezami *et al.* (2021) investigated decentralised load balancing in SDN networks using multi-level traffic management techniques. They note that the decentralised approach has a significant advantage in the context of variable traffic, since each node can make its own decisions. However, the researchers also pointed to the problem of increasing delays and load on nodes with a very large number of connected devices. These findings partially coincide with the current ones, since the high level of adaptability of the decentralised approach to variable traffic was equally indicated. However, the current study highlights the additional difficulties associated with optimising power consumption and integrating with NFV technologies, which was not emphasised by researchers. However, decentralised systems require more sophisticated algorithmic provisioning to maintain network balancing, which can increase the load on individual nodes and cause delays with high traffic volumes.

X. Jiang *et al.* (2021) examined the effectiveness of using distributed balancing methods, including hashing-based algorithms for traffic distribution. They obtained a result that showed that distributed balancing gives better results in large, heavily loaded networks compared to centralised control. This confirms current conclusions about the importance of flexibility and scalability in networks, but the researcher did not consider power consumption and its impact on overall system efficiency. In the current results, energy efficiency was an important component.

One of the most important aspects of the study was the use of machine learning technologies to predict traffic and optimise balancing processes. Algorithms that can predict

network loads can reduce the likelihood of overloads and optimise resource usage. S. Liang *et al.* (2020) examined the role of machine learning algorithms in load prediction for traffic balancing in SDN networks. They found that using machine learning can reduce the likelihood of network congestion by predicting the load using models based on historical data. However, they also noted that the accuracy of such forecasts depends on the quality and relevance of training data. This is especially true for complex and dynamic networks, where changes in traffic can be unpredictable. The results are completely consistent with current data on the importance of machine learning for load forecasting. Both studies pointed to limitations related to the relevance of data, but the current one has added an aspect of using hybrid approaches to improve adaptability to new situations, which the researchers did not provide.

The study also drew attention to aspects of energy efficiency in load balancing. The use of NFV technologies reduces power consumption by virtualising network functions, which reduces the need for specialised hardware. However, when using virtual load balancers, there may be an increase in power consumption compared to conventional hardware solutions. T.V.K. Buyakar *et al.* (2019) investigated the efficiency of using network function virtualisation for load balancing. They concluded that virtualisation can significantly reduce hardware costs and improve network scalability. However, virtualisation processes can be energy-intensive and require additional optimisation to maximise efficiency. The researchers' findings coincide with the current results regarding the energy intensity of virtualisation and the need to optimise it. However, in the current study, more attention is paid to integrating NFV with other technologies to improve energy efficiency, which was not indicated in the paper by T.V.K. Buyakar *et al.* This indicates the need for additional optimisation of energy aspects in the design of networks based on SDN and NFV. R. Moosavi *et al.* (2021) investigated the effectiveness of SDN and NFV integration in the context of energy conservation. They found that these technologies can reduce the overall power consumption of networks, but require detailed configuration to avoid unnecessary power consumption due to excessive virtualisation. The results of the study under consideration and the current one partially coincide in terms of energy consumption. However, the current study focuses more on load balancing, and it notes that energy aspects are only part of the overall network optimisation strategy. The integration of these technologies with other modern methods, such as multichannel or hybrid networks, opens up new opportunities for achieving greater flexibility and scalability. For example, using hybrid cloud environments with dynamic resource allocation capabilities can further improve load balancing efficiency.

U.K. Jena *et al.* (2022) focused on comparing different load balancing methods in hybrid networks that use both physical and virtual resources. They found that hybrid networks can provide high flexibility and adaptability, but the complexity of managing such networks increases significantly.

Comparison with current results shows similarities in understanding the importance of flexibility in load balancing, but emphasis has been added on using machine learning to improve the management of such networks, which is a more detailed approach in the current study. O. Pidpalyi (2024) analysed the prospects for integrating machine learning algorithms to optimise routes and traffic in the telecommunications industry. According to his conclusions, the use of these technologies helps to increase network performance by reducing latency and improving throughput by predicting traffic changes based on historical data. This is very similar to the current results, which also focused on using machine learning to predict the load, but the researcher did not consider factors such as power consumption and cost of calculations when implementing such algorithms. A.A. Ibrahim *et al.* (2020) investigated the application of load balancing methods using a centralised controller in SDN/NFV environments. The main focus was on reducing latency and power consumption, which are also important aspects in this paper. However, in contrast to the current results, the researcher did not factor in changing load conditions and mainly considered stable traffic, which limits their approach to dynamic networks. They also emphasised the importance of using less energy-intensive methods, such as those with the lowest latency, which is partly similar to current data on energy efficiency, but his method provided less flexibility when adapting to changes in traffic.

Based on the results of the discussion, it can be concluded that the optimal approach to load balancing depends on the specific conditions and requirements for the network. In the future, it is worth continuing to work on integrating machine learning to provide greater flexibility and efficiency in balancing processes. SDN and NFV technologies have great potential to improve network performance, but it is necessary to consider the specifics of infrastructure and traffic to maximise their efficiency.

Conclusions

The study was aimed at comparative analysis of load balancing methods based on SDN and NFV technologies, with an emphasis on their efficiency and compliance with modern requirements for energy efficiency and adaptability in

dynamic traffic conditions. As a result of the analysis, it was revealed that centralised management methods have advantages in energy consumption, but they are inferior in performance in conditions of distributed resources. In addition, decentralised approaches, although require higher power consumption, provide high adaptability, which makes them optimal for scenarios with high resource allocation. The method of the lowest delay has shown its effectiveness in conditions of stable traffic, while meeting the requirements of energy efficiency.

The study showed that SDN/NFV is the most effective for such networks. They combine centralised and decentralised management architectures, providing a balance between power consumption and adaptability in a variable traffic environment. Such methods can provide high performance, reduce latency, and optimise power consumption depending on specific usage conditions. In addition, combined approaches help to reduce infrastructure costs and improve overall network efficiency. Overall, the study confirmed the importance of considering energy constraints and dynamic traffic requirements when choosing balancing methods in SDN/NFV networks, which can significantly increase their efficiency and productivity, and optimise energy and resource costs in the face of constant data growth.

The prospects for further research are to expand scenarios for testing load balancing methods in real-world environments, in particular in 5G, IoT, and cloud computing networks, and to implement machine learning for automatic traffic optimisation. In addition, an important area is to improve the energy efficiency of decentralised systems and integrate SDN/NFV with the latest technologies, such as blockchain and quantum computing.

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Conflict of Interest

None.

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Порівняльний аналіз методів балансування навантаження на основі SDN/NFV

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Аспірант

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Анотація. Метою дослідження було визначення переваг та недоліків застосування методів балансування навантаження в мережах на основі технологій Software-Defined Networking та Network Functions Virtualization. Окрему увагу було приділено порівнянню ефективності різних підходів до балансування, зокрема централізованих та дистрибутивних методів, а також використанню інтелектуальних алгоритмів для прогнозування навантаження. Аналіз дозволив визначити переваги та недоліки кожного з методів, а також їхні можливості для адаптації до змінних умов мережевого трафіку, з урахуванням таких параметрів, як пропускна здатність, затримки, втрата пакетів та енергоефективність. У роботі розглянуто методи балансування навантаження в мережах на основі технологій Software-Defined Networking та Network Functions Virtualization, які є важливими для забезпечення ефективності, масштабованості та адаптивності сучасних мереж. Описано ключові виклики, з якими стикаються ці технології, такі як динамічність і непередбачуваність трафіку, оптимізація ресурсів, енергоефективність, а також інтеграція інтелектуальних алгоритмів для прогнозування навантаження і зменшення енергоспоживання. У дослідженні представлено порівняння різних методів балансування навантаження, включаючи централізоване та дистрибутивне управління трафіком, а також використання віртуальних балансувальників і адаптивних алгоритмів переспрямування трафіку. Особливу увагу приділено аналізу впливу цих методів на пропускну здатність, затримки, втрати пакетів і енергоефективність у різних умовах трафіку. Розглянуто роль машинного навчання в оптимізації процесів балансування навантаження, а також можливості інтеграції Software-Defined Networking та Network Functions Virtualization у гібридні мережі. Згідно з результатами дослідження, використання методів балансування на основі Software-Defined Networking/Network Functions Virtualization дозволяє значно підвищити ефективність мереж, зменшити затримки та збільшити пропускну здатність, при цьому знижуючи енергоспоживання в умовах високих навантажень. Виведено ключові результати для України, де інтеграція Software-Defined Networking/Network Functions Virtualization у телекомунікаційну інфраструктуру може стати основою для підвищення якості послуг, оптимізації витрат та забезпечення високого рівня безпеки в умовах цифрової трансформації та модернізації інфраструктури

Ключові слова: віртуалізація функцій мережі; інтелектуальні алгоритми; оптимізація ресурсів; гібридні структури; енергоефективність