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Optimising service quality and network efficiency in legacy networks by integrating SDN and broadband

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Abstract. The study aimed to develop an empirical model for optimising the quality of service (QoS) and improving the efficiency of telecommunications networks by integrating software-defined networking (SDN) and broadband Internet access technologies. The study employed simulation modelling, scenario analysis and analytical models with the use of modelling tools. The main findings of the study highlighted the significant potential of integrating SDN and broadband technologies to improve the QoS and efficiency of telecommunications networks. SDN concepts were demonstrated, which provide centralised network management and flexibility in configuration, as well as broadband access, which offers high data rates and improved bandwidth. The role of each network element, including routers, switches and controllers, and their impact on network efficiency was identified. An analysis of the interaction of SDN with broadband access networks has shown that the use of such networks allows optimising routing, load balancing and traffic management, which helps to improve network speed and reliability. QoS metrics demonstrated that the integration of different technologies leads to significant improvements in bandwidth, packet loss, latency and latency variability. In general, the network model showed the effectiveness of SDN and broadband integration in optimising network performance and QoS, and a review of network modelling methods showed that the use of simulation tools allows for a detailed assessment of the effectiveness of technology integration and confirmation of their positive impact on network performance. Thus, results confirmed that the integration of SDN and broadband technologies significantly improves the efficiency of telecommunications networks, which indicates the effectiveness of new technologies in increasing the overall performance of networks

Keywords: software management; wireless technologies; resource virtualisation; capacity analysis; adaptive systems

Introduction

The growth in traffic volumes and the diversity of applications in networks create new requirements for quality of service (QoS) and network management efficiency. Traditional network architectures often face limitations in delivering the high data rates, reliability and scalability required to support applications. There are also difficulties in integrating new technologies, such as software-defined networking (SDN) and broadband, into existing network infrastructures. The main challenge is that the integration of these technologies requires effective management and optimisation techniques that can cope with instability and latency, and balance data rates and QoS.

In general, SDN is an innovative computer network management architecture that revolutionises the traditional approach to network administration by separating management and data transmission functions. The main components of SDN are a controller, a southbound interface and a northbound interface. The SDN controller is the central element of the system, responsible for global network management, policy enforcement and decision-making. It communicates with network devices via a southern interface, usually implemented using the OpenFlow protocol. The Northern Interface provides communication between the controller and applications or services, allowing them to access network resources and functions.

Broadband access networks are critical to providing high-speed and continuous Internet connectivity in a variety of environments, including residential, commercial and institutional. The main types of broadband networks include fibre-optic networks, which provide extremely high

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data transfer speeds using light signals through optical fibres. Cable networks use coaxial cables to transmit data, television signals and voice services. Digital Subscriber Line (DSL) uses existing telephone lines to provide broadband access at different speeds depending on the distance to the site. Wireless technologies provide connections via radio waves and mobile networks that use cellular base stations to provide mobile Internet access.

The integration of SDN and broadband technologies is a key aspect of increasing the efficiency and adaptability of modern telecommunications infrastructures. SDN allows for centralised network management, which enables flexible and dynamic configuration of network resources, reducing the need for manual intervention and enabling faster response to changing requirements. In turn, integration with various broadband technologies allows for optimised load balancing, improved QoS and reduced latency, which is critical to ensuring a high-speed and reliable Internet connection.

The analysis of similar studies is key to determining the direction of further research and addressing existing gaps in the field. For example, the work of I. Dulska (2019) showed the problems of adapting broadband access statistics in Ukraine to international standards, pointing out the inconsistency of national indicators with European criteria and the fragmentation of data, which makes it difficult to accurately assess and compare broadband speeds and coverage. M. Vasylkivskyi *et al.* (2023) demonstrated that the introduction of SDN and drone technologies has opened new opportunities for network optimisation in challenging environments, noting significant improvements in QoS and network efficiency. In addition, V.I. Drovovozov *et al.* (2022) investigated methods for integrating heterogeneous 4G and 5G wireless networks to improve QoS.

S.A. Trivedi (2024) considered cross-layer design methods that can improve communication between layers and overall network efficiency, including optimising its performance and traffic management. D. Sarabia *et al.* (2024) showed an architecture for integrating Recursive Inter-Network Architecture (RINA) with SDN, which reduced the barriers to RINA implementation on the Internet of Things (IoT) environment through the use of distributed applications and virtual private networks. S. Khan *et al.* (2021) developed a new approach to resource management in 5G networks based on SDN and Network Function Virtualisation (NFV), proposing a new resource management policy. Additionally, M. Lonare Mahesh & M.S. Devi (2022) applied modern genetic algorithms to detect and manage congestion in SDN-based networks, which allows for more efficient management of network traffic and reduced network load.

Moreover, M. Aboughaly & S.A. Hannan (2024) addressed QoS optimisation in SDN with a system that demonstrated a significant advantage over traditional QoS solutions. H. Ma *et al.* (2024) presented a new SDN controller along with a routing algorithm based on multi-criteria optimisation, which significantly improved the throughput in satellite networks. D.S. Sahana & B. Savadatti (2024) proposed a new architecture for secure authentication and access control in SDN for IoT, which provided increased network security and efficiency.

The study aimed to develop a model for improving the QoS and efficiency of telecommunications networks by integrating SDN and broadband Internet access technologies. To this end, the following tasks were performed: a comprehensive analysis of the implementation of SDN technologies to optimise access to broadband networks, an assessment of the impact of SDN integration on increasing the speed, efficiency and reliability of networks, a study of practical examples of successful SDN implementation in telecommunications systems, and an analysis of the main problems and challenges encountered when integrating SDN with broadband Internet access.

Materials and Methods

First, a theoretical overview of the concepts of SDN and broadband access was conducted. For this purpose, an analysis of existing scientific publications in this area was carried out. The concepts of SDN were learned through documentation on centralised network management and its flexible capabilities.

The analysis of broadband access networks included a detailed description of different types of networks, such as fibre-optic, DSL and cable modems, with a focus on their ability to provide high data rates and scalability. In this context, the study addressed how SDN-technologies affect the overall performance of the network, their main advantages and capabilities.

All key elements of networks, including routers, switches, controllers, access points, were described. Their role in solving network problems, such as routing, load balancing and traffic management, was considered. It identifies how each component contributes to the overall goal of optimising and improving network efficiency.

Next, the study investigated the possibilities of implementing SDN to optimise a broadband access network. Simulation modelling techniques were used to assess the effectiveness of SDN implementation in various broadband access scenarios. For this purpose, network models with different SDN and broadband access configurations were set up to assess the impact of these technologies on network speed, efficiency and reliability.

Particular attention was devoted to the analysis of the impact of SDN on aspects such as routing optimisation, load balancing and traffic management. It was assessed how SDN can improve these processes by providing more efficient resource management and reducing delays and packet loss. In addition, the main areas of broadband network optimisation were discussed, and examples of practical use of SDN in broadband networks were provided.

At the stage of assessing the impact of the integration of SDN and broadband technologies on QoS indicators, a detailed analysis of various metrics that determine network efficiency was carried out. The following key metrics were used for this purpose:

1. Bandwidth (BW) (1):

$$BW = \frac{T}{D}, \quad (1)$$

where D – amount of data transmitted during the time T.

2. Delay (Del) (2):

$$Del = PpDel + TDel + QDel + PcDel, \quad (2)$$

where $PpDel$ – signal propagation delay over the network, $TDel$ – delay in data transmission through the communication channel, $QDel$ – queuing delay in network devices, and $PcDel$ – data processing delay on routers.

3. Packet Loss (PL) (3):

$$PL\ Rate = \frac{L}{T} \times 100\%, \quad (3)$$

where L – number of lost packets during the time T.

4. Jitter (J) (4):

$$J = SD\ of\ Del, \quad (4)$$

where SD – standard deviation.

For each of these metrics, the performance before and after the introduction of SDN and broadband technologies was compared. A significant increase in throughput, a decrease in latency and latency variability, and a reduction in packet loss were noted.

The network was modelled using the Diagrams.net platform, which was used to build a network diagram. Simulation tools such as Simulink, Network Simulator 3 (NS-3), OMNeT++, Mininet and Graphical Network Simulator 3 (GNS3) were also analysed. These tools were chosen due to their ability to create virtual network models and analyse their operation in conditions close to real-world conditions. Simulink was used to build and analyse the service request flow model. NS-3 and OMNeT++ provided an in-depth analysis of network protocols and network behaviour. Mininet was used to analyse virtual networks using real network components and protocols. GNS3 was used to analyse the integration of real network devices and virtual models, which made it possible to evaluate the effectiveness of SDN implementation in real-world conditions, considering the specifics of specific equipment and configurations.

Results

SDN is an innovative architecture that enables centralised network management through software interfaces. This concept differs from traditional network architectures in that it separates the control layer from the forwarding layer, allowing for more flexible network management and configuration.

The main components of SDN include a controller, peripherals, applications, and north and south Application Programming Interface (API). The controller is the central element of the SDN architecture, which is responsible for managing the network and coordinating actions between different components. It receives information from network devices and uses it for traffic routing decisions. Edge devices are network switches that perform traffic-forwarding functions based on instructions from the SDN controller. They do not have internal routing algorithms and always rely on the controller's instructions.

Applications, in turn, are software applications that use SDN capabilities to implement various functions, such as virtual networks, load balancing, etc. As for the API, it can be north and south, where the north API is an interface for the SDN controller to interact with applications and services, which allows applications to interact with the controller to configure and monitor the network. The southern API is an interface for the controller to interact with peripherals, usually using the OpenFlow protocol to send commands to switches.

The SDN architecture consists of a controller that centrally manages the network, using a northbound API to interact with applications and a southbound API to manage network devices such as switches. Applications manage the network through software configuration, which provides abstraction of the physical infrastructure and centralised management of the entire network (Fig. 1).

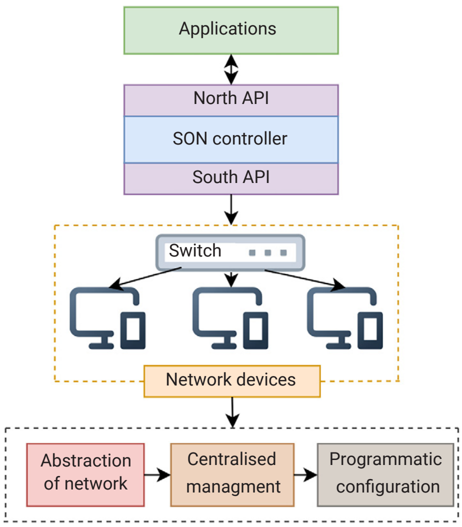

Figure 1. SDN architecture diagram
Source: compiled by the author

In general, SDN is widely used in various fields due to its unique capabilities. In data centres, SDN is used to create flexible and scalable networks, which provide efficient management of many resources and high performance. In cloud computing, SDN helps to dynamically allocate resources and ensure high availability of services. This is important for maintaining high QoS standards and efficient resource utilisation. Operator networks are also using SDN to introduce new services and improve the efficiency of their networks. This allows operators to adapt more quickly to changing user needs and improve their network infrastructures.

In addition, SDN can be implemented in enterprise networks to dynamically manage resources and improve QoS. For instance, in conditions of high traffic volatility, during large online events, SDN can automatically reallocate network resources in real-time, providing priority access to resources for critical applications and services. This will reduce latency and avoid network congestion, ensuring stable performance even during peak loads.

In a 5G network environment, SDN can be used for intelligent traffic management, particularly in IoT and autonomous vehicle scenarios. SDN enables more precise traffic management based on the specific QoS requirements of different types of data, such as data from IoT sensors, video streams from surveillance cameras, or data from vehicles. This approach can increase the efficiency of network resources and improve overall network performance.

In cloud data centres, SDN can be used to orchestrate network operations more efficiently. This can include automated deployment of virtual networks, configuration of security policies, and monitoring of network traffic. For example, in cloud environments where resources are shared by many users at the same time, SDN can enable dynamic changes to the network topology based on user needs, which can improve performance and minimise latency.

In smart cities, SDN can provide centralised management and integration of various city services, such as transport, energy, security and communications. By using SDN, a flexible and scalable infrastructure that can adapt to the growing number of connected devices and ensure reliable operation of city services can be created. This can include dynamic traffic routing based on real-world conditions in the city, such as traffic congestion or accidents.

Broadband networks are the infrastructure that provides high-speed Internet access to end users. They are critical to modern communications systems as they provide the necessary bandwidth for real-time data, voice and video transmission. The following components of broadband access networks should be distinguished: access networks and wireless access technologies (Table 1).

Table 1. Types of broadband network technologies and examples of their use

Types of technologies	**Description of access network technologies**	**Examples of use**
DSL	A technology that uses existing telephone lines to transmit data at high speeds. DSL provides high download and upload speeds at relatively low costs	Home networks in rural areas
Cable modems	They use coaxial cables to provide Internet access. Thanks to the high bandwidth of coaxial cables, cable modems can provide fast, high-bandwidth Internet access.	Internet in residential complexes
Optical fibres	Fibre-optic networks provide the highest speed and lowest latency for data transmission. They use light pulses to transmit information through glass or plastic fibres, which enables extremely high speeds and large data volumes	Enterprises, data centres, urban infrastructure
Types of technologies:	**Description of wireless access technologies**	**Examples of use**
Wi-Fi	A technology that provides wireless access to the Internet via radio waves. Wi-Fi is often used in home and office networks to connect to the Internet without having to run physical cables.	Home and office networks, cafes, airports
Mobile communications (3G, 4G, 5G)	Mobile networks provide Internet access through mobile towers that cover large areas. With the advent of 5G, there are opportunities for even faster and more reliable access with less latency.	Mobile internet, smart cities, autonomous cars

Source: compiled by the author

Broadband networks are made up of various elements, each of which performs specific functions to provide efficient and reliable Internet access. The main elements include network equipment, access points, network infrastructure, and network solutions based on various technologies. Figure 2 presents a diagram illustrating the main elements of broadband access networks.

Network equipment includes modems, routers and switches (Fig. 3). Modems are key components in broadband access networks that modulate and demodulate signals. They provide a connection between the user's local network and the provider's access network. There are different types of modems depending on the access technology, such as DSL modems for telephone lines and cable modems for coaxial cables. Routers are responsible for routing traffic between different networks. They decide how and where to route data to ensure optimal speed and reliability. Routers also provide connections between the local network and the Internet, as well as between different devices within the local network. In turn, switches ensure efficient data transmission within the local network. They operate at the link layer of the Open System Interconnection model and perform the function of exchanging data between different devices within the same network. Switches connect various devices, such as computers, printers, and servers, to the network.

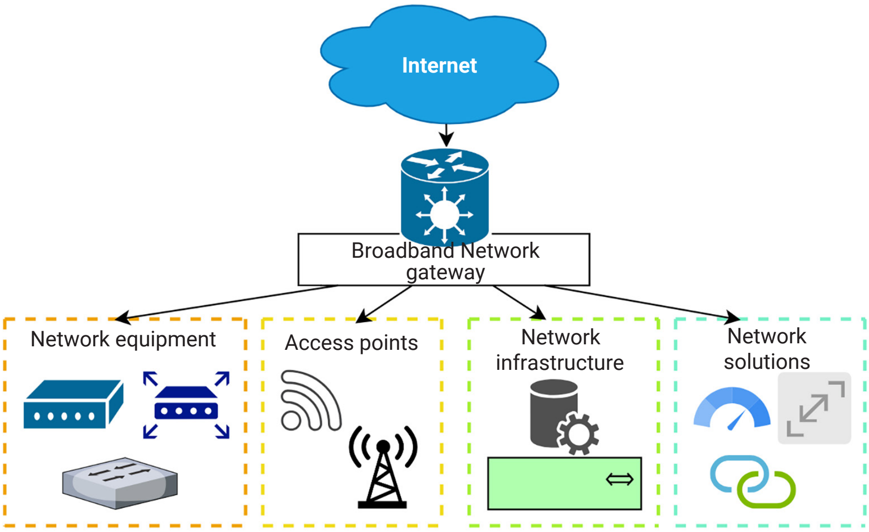

Figure 2. Diagram of the main elements of broadband access networks
Source: compiled by the author

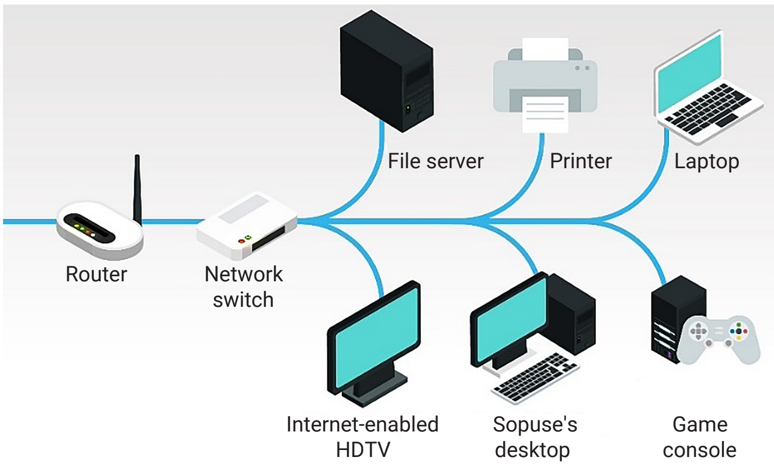

Figure 3. Usage of network equipment devices
Source: Modem vs router vs switch: How to choose (2024)

Wireless access points connect devices to wireless networks. They broadcast radio signals that can be picked up by wireless devices such as laptops, smartphones and tablets. Access points provide mobility and convenience, allowing users to connect to the Internet without the need to run physical cables.

In mobile networks, base stations provide the connection between mobile devices and the operator's central network. They cover territories and allow mobile users to connect to the Internet via mobile networks. As for the provider's central office, it is the main point of connection between the local networks of users and the global Internet. This is where data is processed and routed and access to the Internet is provided. Routers, switches and other network components are in the provider's office.

Distribution networks are responsible for transferring data from the central office to end users. They can include optical fibres, coaxial cables or other types of connections that enable the transmission of large amounts of data at high speeds. The main objective of broadband access networks is to provide high speed and bandwidth for data transmission. This is achieved using various technologies and components, such as optical fibres for fast data transmission and routers for efficient traffic routing.

To ensure reliable connectivity, network equipment and infrastructure must be designed to minimise potential failures and outages. This includes redundant components, network monitoring and rapid response to problems. In addition, broadband networks must be scalable to support the growing number of users and traffic volumes. This is achieved through a modular architecture and the ability to add new components and technologies as needed.

The main advantages and capabilities of these components in the context of telecommunications are flexibility and adaptability, centralised management, resource optimisation and the ability to refute the introduction of new services. In other words, SDN can be used to quickly adapt a network infrastructure to changing conditions.

Centralised control and software management can be used to easily reconfigure the network without the need for physical intervention. The SDN controller provides a single point of control for the entire network, which simplifies administration and can be used to manage traffic and security policies more efficiently. Software-based management optimises the use of network resources by dynamically adjusting routing and load balancing, which improves overall network performance. Moreover, SDN allows for the rapid introduction of new services and applications through easy integration with additional applications via a northern API. However, there are also certain limitations (Table 2).

Table 2. Advantages and limitations of broadband network technologies

Types of technologies	Advantages of access network technologies	Limitations of technology
DSL	DSL provides cost-effective access to the Internet with sufficiently high data transfer speeds, which reduces infrastructure costs while maintaining good speeds	Dependence on the quality of telephone lines, limited speed and range from telephone exchanges
Cable modems	The high bandwidth of coaxial cables provides fast Internet access, and cable modems can support large volumes of traffic, which is important for users with high-speed requirements.	Dividing the channel between users can reduce speed during peak hours
Optical fibres	Fibre-optic networks provide the highest speed and lowest latency of data transmission, which is critical for modern telecommunications, where speed and large volumes of data are important	High cost of installation, difficulty in laying cables
Types of technologies:	**Advantages of wireless access technologies**	**Limitations of technology**
Wi-Fi	Wireless Wi-Fi access points provide convenient access to the Internet without the need to lay cables, which is especially important for home and office networks where mobility and ease of connection are critical.	Limited coverage area, slower speed with distance from the router, sensitivity to interference
Cellular communications	Cellular networks provide Internet access over large areas, allowing users to stay connected wherever they are	Depending on the operator's coverage, the price can be high, with lower speed during peak hours.

Source: compiled by the author

In addition, the central office is an important point for managing and controlling the entire network, including routing and traffic distribution, which contributes to stability and efficiency. Distribution networks ensure efficient distribution of traffic from the central office to end users, which is important for scaling and ensuring high QoS in the face of growing loads.

The introduction of SDN into broadband networks can significantly improve their performance, including optimising speed, efficiency and reliability. SDN allows for centralised network management through a controller that coordinates and configures all network components from a single location. This makes it easier to manage configurations and optimise resources, as administrators do not need to manually configure each network element. For broadband networks, this means the ability to quickly adapt to changing traffic conditions and user needs.

Using SDN for dynamic routing and load balancing can significantly improve data transmission efficiency. SDN controllers can implement routing algorithms that automatically respond to changes in traffic, preventing congestion and ensuring optimal use of network resources. In addition, SDN allows for the integration of network analytics tools to monitor and analyse traffic in real-time. This allows administrators to obtain data on the network status, detect anomalies and adjust in real-time, which increases network efficiency. It is also worth addressing the main areas of broadband network optimisation using SDN (Fig. 4).

The benefits of implementing SDN include improved speed and efficiency, increased network reliability, flexibility and scalability. SDN can be used to implement mechanisms to optimise data rates, such as adaptive routing and QoS management. This ensures high speeds and reduces network latency, which is important for providing high-quality broadband access.

Furthermore, SDN controllers can provide automatic troubleshooting, which improves network reliability. The quick response to problems and resource reservation reduces downtime and improves overall network stability. In addition, the implementation of SDN simplifies the scaling of the network to meet growing demands and needs. Thanks to the centralised management capabilities, new technologies and services can be quickly integrated without significant effort and cost to redesign the network infrastructure.

In addition to the benefits, there are also certain challenges to implementing SDN, including compatibility with existing infrastructure, security and governance, and complexity of configuration and management. In other words, one of the main challenges is the integration of SDN with existing network infrastructure, especially in older systems. It is necessary to ensure compatibility between new SDN components and old equipment, which may require additional costs and time.

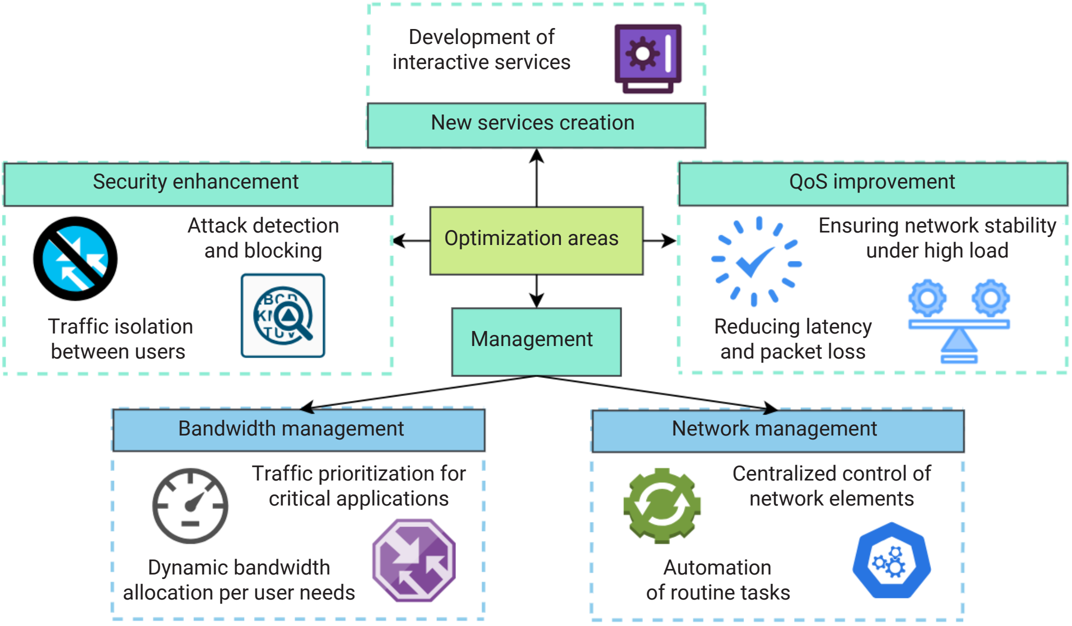

Figure 4. Key areas of broadband network optimisation

Source: compiled by the author

SDN poses new security challenges as centralised control can become a target for attacks. The SDN controller needs to be protected and counteracted, which requires additional security and monitoring measures. While SDN provides centralised management, configuring and managing new technologies can be a complex process that requires specialised knowledge and skills. This can lead to the need for additional training for technical staff and support from vendors.

Examples of SDN use in broadband access networks:

- virtual networks (creation of virtual networks for different types of users);
- load balancing (traffic distribution between several servers to increase availability);
- QoS (providing guaranteed QoS for critical applications);
- configuration automation (automatic network setup when adding new users or devices).

Implementation of SDN in a broadband network has significant potential to optimise its performance but requires careful planning and consideration of challenges. For a more detailed understanding, it is also necessary to analyse the impact of SDN on improving network speed, efficiency and reliability (Fig. 5).

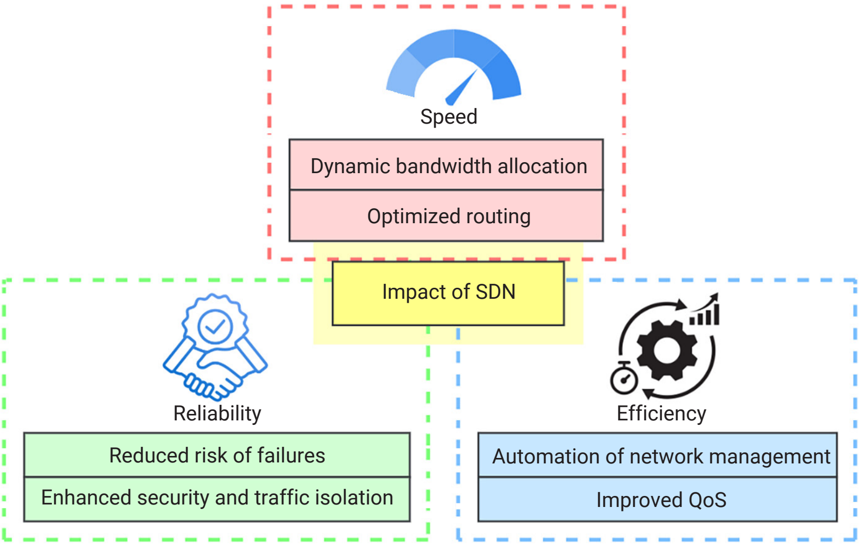

Figure 5. SDN impact on improving network speed, efficiency and reliability

Source: compiled by the author

As such, SDN can be used to dynamically allocate bandwidth to users based on their needs, which ensures optimal data transfer speeds. Centralised routing management with an SDN controller can be used to find the most efficient routes for traffic faster, which reduces latency and increases data transfer speeds.

SDN also automates routine operations, such as network configuration and monitoring, which reduces the human factor and increases the overall efficiency of network management. Using SDN to allocate resources based on traffic priorities can increase bandwidth efficiency and provide better QoS for critical applications.

Moreover, centralised management of network elements identifies and resolves problems faster, reducing the likelihood of outages and improving overall network reliability. SDN can also be used to implement traffic isolation and attack detection mechanisms, which protect the network from external threats and ensure stable operation under high load conditions.

QoS in telecommunications networks is a critical factor in ensuring high data transfer speeds, reliability and overall network efficiency. The main QoS parameters include throughput (Formula 1), latency (Formula 2), packet loss (Formula 3) and delay variability (Formula 4). The integration of SDN and broadband technologies can have a significant impact on these parameters, thanks to the ability to centrally manage and flexibly allocate network resources.

SDN integration can be used for optimised routing and load management, which reduces overall latency. Once integrated, centralised management provides better utilisation of available resources, which can increase throughput. SDN provides better control of traffic and reduces the likelihood of packet loss by optimising routes and managing load. Variability, in turn, is measured as the standard deviation of delays between packets, and SDN helps reduce this variability through more stable traffic management.

Thus, integrating SDN with broadband Internet access allows for increased bandwidth, reduced and stable latency, and reduced packet loss. With centralised management of the SDN network, resources can be more efficiently allocated to different users and services, which helps to increase throughput. Optimised route and load management help to reduce data latency as SDN enables faster and more efficient response to changing network conditions. Thanks to improved traffic management and the ability to adaptively re-plan routes, the likelihood of packet loss is reduced. At the same time, reduced latency variability due to routing optimisation and load management makes the connection more reliable and stable.

The integration of SDN technologies with broadband access has a significant impact on QoS. It is possible to demonstrate how to use a formula to calculate bandwidth. For instance, before the introduction of SDN and broadband access, the amount of transmitted data was 5,000 MB and the transmission time was 100 seconds, then, based on the formula, the throughput would be 50 MB/s. If, after the implementation, the amount of data transferred is 6,000 MB and the transfer time is 100 seconds, then the throughput will be 60 MB/s. The increase in bandwidth can be calculated as a percentage increase from the previous value. Thus, the introduction of SDN and broadband access has increased bandwidth by 20%. Similarly, it is worth analysing latency, packet loss and latency variability (Fig. 6).

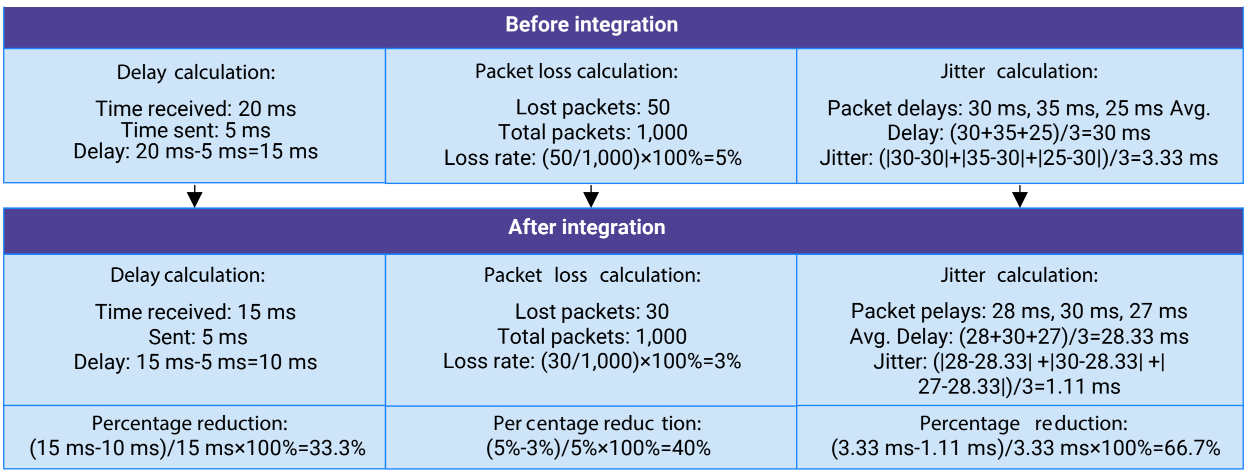

Figure 6. Examples of basic QoS parameter calculation

Source: compiled by the author

This diagram shows that the introduction of SDN and broadband access has reduced latency by 33.3%, packet loss by 40%, and delay variability by 66.7%. The introduction of SDN and broadband has led to a significant reduction in network latency. This was made possible by improved traffic routing and optimised data paths. The integration of SDN with broadband technologies has also reduced packet loss. Packet loss is a critical metric for QoS as it affects data integrity and recovery. Another important change is the reduction in latency variability. This is an indicator that reflects the fluctuations in delay during packet transmission.

In general, the introduction of SDN and broadband access has significantly improved key QoS indicators, which ensures more efficient and reliable operation of modern telecommunications networks. Network modelling is a key aspect in the design and optimisation of telecommunications systems, especially when integrating SDN and broadband. The key elements of the SDN architecture are the basis for modelling and subsequent optimisation of network QoS and efficiency, especially when integrated with broadband Internet access (Fig. 7).

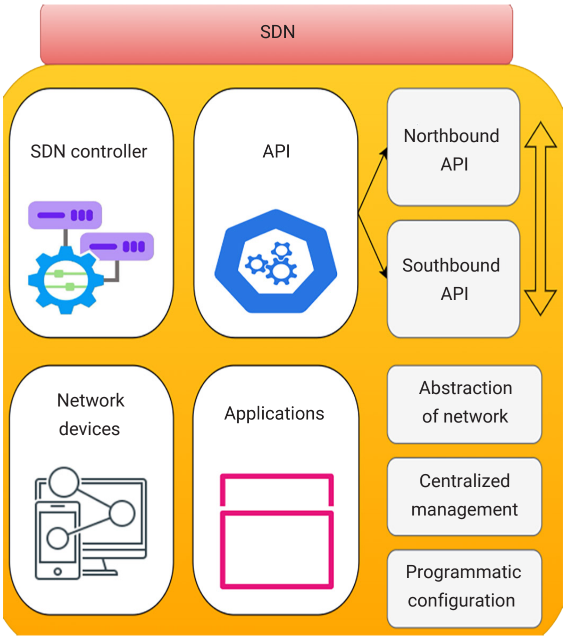

Figure 7. SDN elements in the network structure diagram
Source: compiled by the author

These elements include a controller, north and south interfaces, network devices and applications that provide centralised management and control over the network, allowing for modelling various scenarios of its operation, considering changes in traffic, loads, and other network conditions. In turn, network abstraction can be used to create virtual environments for testing various scenarios without having to change the physical infrastructure, and centralised management enables constant network metrics monitoring and subsequent analysis to assess efficiency and QoS during simulations.

At the same time, the SDN controller also contains several key components, such as a network management module that centrally controls network devices and traffic, a policy module that implements traffic and security rules, a monitoring and analytics module that monitors the network status in real-time, and a security module that protects the network from threats.

In addition, broadband Internet access is important, because, in network modelling, its elements are central to ensuring high-quality user access to the network through various technologies (Fig. 8).

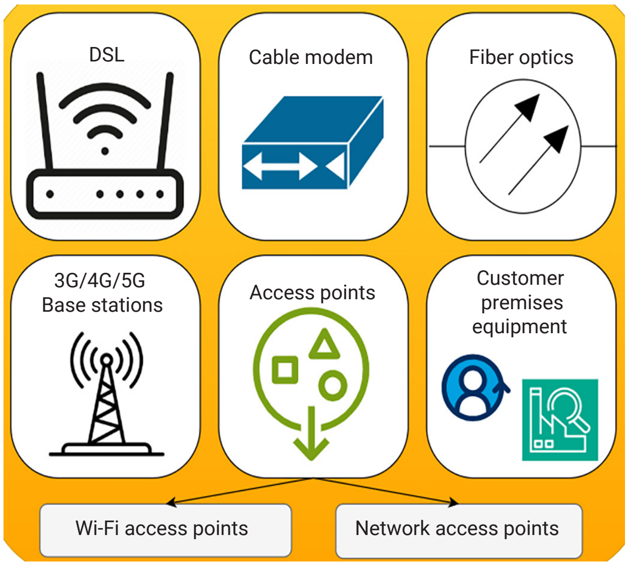

Figure 8. Components of broadband Internet access
Source: compiled by the author

DSL and cable modems provide Internet access through existing copper or coaxial cables, which can significantly reduce connection costs and provide stable access over long distances. Optical fibres are used to provide the highest data transfer speeds with minimal latency, which is critical for modern networks. In addition, Wi-Fi access points and base stations provide wireless access to the network, allowing users to connect to the Internet from anywhere without depending on physical connections. This is especially important for providing mobility and flexibility of access, which is critical for the modern user. Subscriber equipment is the endpoint device that provides connectivity to the network, while network access points are responsible for combining different access technologies into a single network infrastructure.

QoS is an important component in network modelling and optimisation, as it is responsible for ensuring the required QoS level for different types of traffic. Traffic management policies help to manage the network according to defined rules, ensuring a balance between performance and QoS. Traffic classification can be used to divide traffic into different categories, which allows the network to adapt to the needs of each type of data. At the same time, traffic prioritisation ensures that mission-critical applications are served with the highest priority, which is important in resource-constrained scenarios. Latency control helps reduce network latency, which is critical for time-sensitive applications such as video conferencing.

Moreover, bandwidth management policies help ensure that resources are distributed evenly among users, especially under high-load conditions. Performance monitoring and analysis provide continuous tracking of network health and performance, which can be used to identify and correct issues that may affect QoS in a timely manner. Furthermore, queue management can be used to control incoming traffic and distribute it according to QoS policies.

The overall structure of the network includes all the above components, making it efficient and adaptable to different operating conditions (Fig. 9). The integration of SDN with broadband access technologies, combined with careful QoS management, allows the network to flexibly respond to changing loads, efficiently allocate resources, minimise latency and ensure stable operation of critical applications. This structure is the key to improving the performance, scalability and reliability of telecommunications infrastructure.

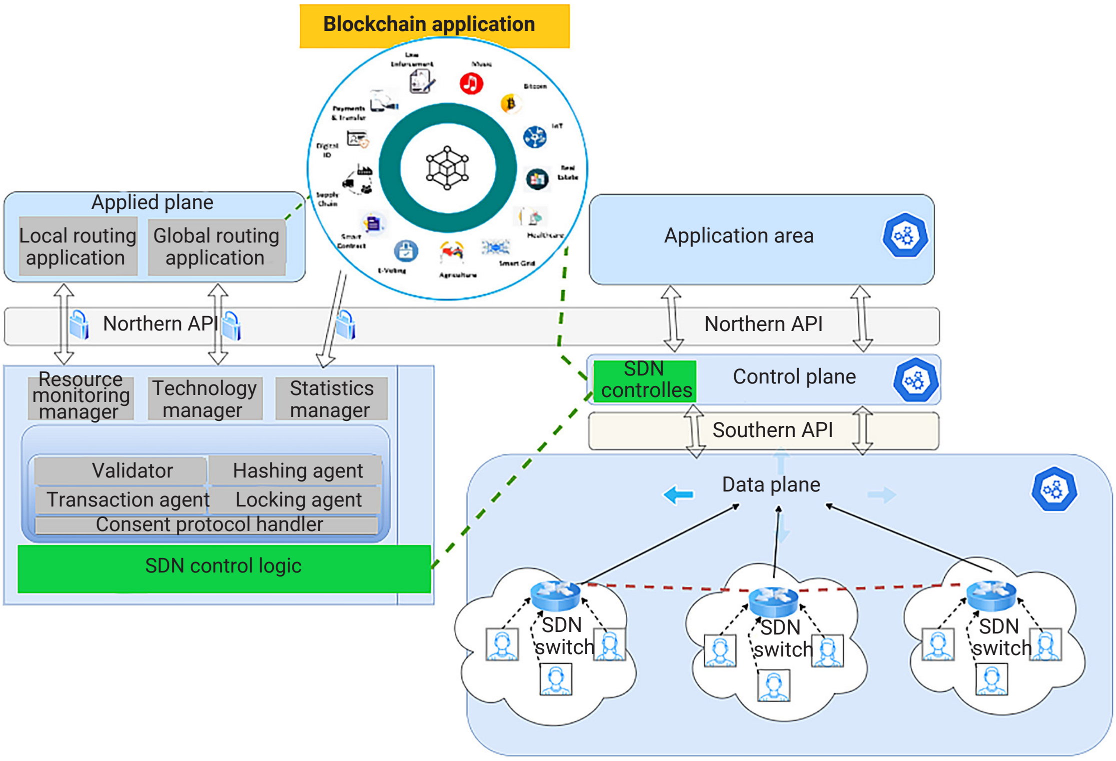

Figure 9. Network structure diagram

Source: compiled by the author

Modern modelling methods and tools should also be considered, as they allow for detailed investigation of how different technologies interact, what their benefits are, and how network efficiency can be improved.

Modelling methods can be divided into simulation modelling, scenario-based analysis and analytical model-based modelling. Simulation modelling involves the use of computer software to create virtual network models (e.g., NS-3 or OMNeT++). Scenario-based analysis involves the development and analysis of various network scenarios (e.g., modelling scenarios with different traffic distributions and SDN parameters). Analytical model-based modelling uses mathematical models and formulas to predict key network parameters (e.g., using analytical models to calculate throughput or latency).

It is also worth exploring modelling tools. For instance, Simulink, a graphical environment for modelling, simulation and analysis of systems, can be used to create models of various types of systems using block diagrams and provides extensive network modelling capabilities. The NS-3 network modelling tool can model both traditional and SDN networks in detail. In turn, the OMNeT++ modular platform creates complex network models and tests their performance in various scenarios. Mininet is a tool for creating virtual networks and testing SDN solutions that can be used to quickly create network models and test their performance in real-time. The GNS3 GUI is a network emulation tool that simplifies the creation and configuration of virtual networks.

Discussion

The study showed that the use of SDN and broadband access optimises traffic and resource management, which has a positive impact on overall network efficiency. The importance of analysing existing research in this area is that it can be used to compare and summarise the results, identify new aspects and confirm the effectiveness of the technologies used in different conditions, which in turn contributes to the further development and improvement of these technologies.

The results of this study showed that the integration of SDN and broadband provides lower latency and higher data rates, which is critical to improving overall network efficiency. C. Zhang *et al*. (2020) proposed a new framework for the dynamic deployment of virtual network functions that reduces resource costs and request rejection rates, which differs from the approach of the previous work, which focuses on improving network speed and reliability. This study also confirmed that SDN can improve traffic management and resource optimisation, while S. Mehraban & R.K. Yadav (2024) addressed the technical and financial challenges of migrating to SDN and the use of algorithms to improve QoS. Their study addresses the problems of traffic management and QoS improvement using new algorithms, which is an additional aspect of the analysis of this study.

This study also demonstrated that the integration of SDN with broadband access networks effectively optimises traffic management, providing improved throughput and reduced latency. In turn, G. Khekare *et al.* (2023) demonstrated models that can achieve 99.4% accuracy in traffic optimisation and access control using synthetic traffic models. The study also confirmed a significant increase in resource management efficiency in real networks, while A. Alioua (2019) demonstrated that the developed algorithms for data processing in automotive networks reduce delays and energy costs. However, the results of the latter work are focused on specific applications, while the present study covered a wider range of applications in broadband access networks.

In contrast to the results of the study, which showed that the integration of SDN with broadband access networks significantly improves the overall network performance, C. He *et al.* (2022) addressed virtual network migration technology that effectively reduces energy costs and increases the request acceptance rate of virtual networks by focusing on energy efficiency instead of network speed and performance. In addition, B.R. Dawadi *et al.* (2022) explored the challenges and solutions for SDN migration, emphasising the importance of security and cost-effectiveness in the transition from traditional networks to SDN, while this study demonstrated how SDN integration improves traffic management and resource optimisation in real-world environments.

While this study showed a significant improvement in traffic management and resource optimisation due to the integration of SDN and broadband, M. Mahajan (2024) analysed the integration of IoT with SDN, focusing on improving flexibility and management efficiency, in the context of smart cities and healthcare, rather than on specific aspects of traffic management and network performance. In turn, R. Kovacs *et al.* (2024) proposed the integration of blockchain technology into an SDN controller to improve service validation, which demonstrates the effectiveness of blockchain technology in SDN management but focuses on ensuring the validation of network functions rather than on the overall improvement of performance and data transfer speed, as in the study.

The results of this study, which demonstrated a reduction in latency and an increase in data transfer speed due to the integration of SDN and broadband, are consistent with the results of a study by A.K. Rangsietti & S.S. Kodali (2022), which addressed the integration of SDN and NFV to optimise cloud environments, which provides scalability and flexibility but does not focus on directly improving data transfer speed. At the same time, in contrast to the results obtained, which focused on improving overall network performance through the integration of SDN and broadband, S.M. Rasool *et al.* (2024) addressed the impact of 5G, SDN and NFV technologies on QoS on the problems of SDN controller placement and their impact on latency, cost and energy efficiency in modern networks.

While this study emphasised the efficiency of resource management and overall network optimisation through the integration of SDN and broadband, M. Klinkowski (2023) focused on modelling and optimising network slice allocation in 5G networks and emphasised the optimisation of resource allocation and traffic transport across networks to provide different types of services with QoS requirements. The results of a study by L. Tang *et al.* (2024) showed a digital twin to improve resource prediction accuracy and reduce latency in SDN/NFV networks and focused on specific aspects of prediction and energy efficiency in the context of IoT. In contrast, this study has confirmed that the integration of SDN and broadband provides a wider range of resource management improvements than the highly specialised approaches considered in other works.

Moreover, the results of the study, which demonstrated an improvement in overall network performance due to the integration of SDN and broadband access, differ from the approaches presented in a study by S. Javanmardi *et al.* (2023) and D. Stilinski & K. Potter (2024). The first study addressed a workflow scheduler for IoT networks that provides protection against attacks and optimises load balancing and latency, showing improvements in response time and network utilisation that focus on security and load-specific aspects rather than overall data rate improvements. Meanwhile, the second study analysed the application of SDN and NFV to the development of flexible 5G core networks, focusing on scalability and automation that reduces costs and improves QoS, but in the specific context of 5G rather than general traffic management and network performance. In comparison, the study covered a broader range of network improvements, providing a comprehensive performance improvement that is not limited to specific aspects of security or scalability.

While the results of this study highlighted the integration of SDN to improve data rates and resource management in the overall network context, the study by P. Kulshreshtha & A.K. Garg (2024) focused on solving the problem of routing and traffic optimisation in 5G networks, comparing the effectiveness of deep learning algorithms to reduce latency and improve network performance. At the same time, the study by H. Ait Oulahyane *et al.* (2023), which proposed a QoS management model for wireless networks that reduces latency and improves resource management, emphasises the effectiveness in specific aspects of QoS management but does not cover a wide range of improvements as in the present study.

The results obtained, which demonstrate an increase in data transmission speed and optimisation of resource management, have common aspects with the work of J. Galán-Jiménez *et al.* (2022), which presents a hybrid load balancing algorithm that effectively balances between reducing energy consumption and balancing traffic in SDN/Internet Protocol (IP) networks. On the other hand, the work of C. Oredola & A. Ashraf (2024) focused on improving the security of IoT networks using SDN controllers. Although this study emphasised that the use of SDN reduces the vulnerability of IoT networks to cyber threats and increases their security, it did not cover aspects of overall network efficiency, in particular, the optimisation of data and resource transfer rates, which is the focus of this paper.

Finally, the common aspects between this study and the works of I. Ikhelef (2024) and S. Kang *et al.* (2024) are the use of SDN to improve network functions and management. However, the first paper focused on integrating SDN with NFV for optimal placement and chaining of virtual functions, while this study focused on integrating SDN and broadband to improve data rates and overall network performance. Similarly, the second paper used graph neural networks to optimise routing in SDN/NFV systems, focusing on latency and computing resource efficiency. While this study's approach also integrated SDN, it considered the broader context, including resource management efficiency and improving overall network performance using broadband.

Thus, a comparison with other studies has shown that while some works focus on NFV or specific aspects of management, this study stands out for its versatility in improving overall network efficiency using broadband. Compared to work that focuses on optimising load balancing or managing resources in specific networks, this approach covers a broader context, providing a comprehensive performance improvement.

Conclusions

The study confirmed that the integration of SDN and broadband significantly improves the overall performance of telecommunications networks. The main results include a significant reduction in latency and improvement in data transfer speeds, which is achieved through efficient traffic management and resource optimisation, as well as improved QoS and the ability to optimise resources. This confirms the potential of this approach to improve network infrastructure, particularly in the context of modern telecommunications systems.

The current research has expanded the understanding of traffic and resource management capabilities in networks to cover a wide range of practical applications. In particular, the study demonstrated that effective management and integration of different network technologies can achieve significant improvements in QoS, which is critical for modern and future networks.

The integration of SDN and broadband access, along with improving QoS, faces several challenges. First, ensuring data security and privacy remains a key challenge, as centralised management over SDN can create new attack vectors. In addition, ensuring scalability and efficiency in the face of increasing workloads and diversity of network resources is a complex task that requires further research.

To further improve the results, it is recommended to introduce algorithms that would reduce the power consumption of network elements, especially under high loads. It is advisable to extend the study to new types of networks, such as 5G and IoT, to confirm the effectiveness of the results in different conditions. The potential of SDN in the context of Wi-Fi 6 networks, edge computing, and blockchain technologies should also be explored, as this will help define the potential of SDN for different types of traffic and network conditions. It is crucial to develop new approaches to protect SDN from potential threats, as centralised management creates new attack vectors. Development prospects include the integration of artificial intelligence to automate network management and improve security technologies.

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Conflict of Interest

None.

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Оптимізація якості обслуговування та ефективності мережі у класичних мережах за допомогою інтеграції SDN та широкосмугового доступу до інтернету

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Анотація. Мета дослідження полягала в розробці емпіричної моделі для оптимізації якості обслуговування та підвищення ефективності телекомунікаційних мереж шляхом інтеграції технологій software-defined networking (SDN) і широкосмугового доступу до інтернету. У дослідженні використано методи симуляційного моделювання, аналізу сценаріїв та аналітичні моделі з застосуванням інструментів моделювання. Основні результати дослідження вказали на значний потенціал інтеграції технологій SDN і широкосмугового доступу. Було продемонстровано концепції SDN, які забезпечують централізоване управління мережею і гнучкість у налаштуванні, а також широкосмуговий доступ, що пропонує високу швидкість передачі даних і покращену пропускну здатність. Виявлено роль кожного елемента мережі, включаючи маршрутизатори, комутатори і контролери, та їх вплив на ефективність мережі. Аналіз взаємодії SDN з мережами широкосмугового доступу показав, що така інтеграція дає змогу оптимізувати маршрутизацію, балансування навантаження та управління трафіком, що сприяє покращенню швидкості і надійності мережі. Показники якості обслуговування продемонстрували, що інтеграція різних технологій веде до суттєвого покращення пропускної здатності, зниження пакетних втрат, зменшення затримок і варіативності затримок. Загалом, модель мережі показала ефективність інтеграції SDN та широкосмугового доступу в оптимізації мережевої продуктивності та якості обслуговування, а огляд методів моделювання мережі підтвердив, що використання симуляційних інструментів допомагає детально оцінити ефективність інтеграції технологій і підтвердити їх позитивний вплив на продуктивність мережі. Таким чином, отримані результати показали, що інтеграція технологій SDN і широкосмугового доступу суттєво покращує ефективність телекомунікаційних мереж, що свідчить про ефективність нових технологій у підвищенні загальної продуктивності мереж

Ключові слова: програмне управління; бездротові технології; віртуалізація ресурсів; аналіз пропускної спроможності; адаптивні системи