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METHODS OF 5G MOBILE NETWORK VIRTUALISATION: ARCHITECTURAL SOLUTIONS AND FUTURE PROSPECTS

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Background. This paper examines approaches to Network Function Virtualisation (NFV) and Software-Defined Networking (SDN) in fifth-generation (5G) mobile networks. It analyses modern implementation methods of these technologies, their role in building a flexible, scalable, and efficient network infrastructure, as well as key challenges and future prospects for their development.

Objective. The paper aims to explore architectural solutions that effectively decouple network functions from hardware, enabling dynamic orchestration and automated resource management. To achieve this, an overview of key models for network function distribution in 5G is provided, including full cloud migration, C-plane migration to the cloud, and a scenario-based approach to load distribution between cloud and mobile infrastructure.

Particular attention is given to network management concepts using SDN, the separation of the control and user planes (C-plane/U-plane), and their impact on network performance, latency, and scalability.

The paper presents a review of current research in 5G standardisation, identifies potential directions for the development of NFV and SDN technologies, and outlines key challenges that require further study to achieve high efficiency and reliability in next-generation mobile networks.

Methods. The study employs an analytical research method that includes the systematisation of existing approaches to network function virtualisation (NFV) in 5G networks. A comparative analysis of architectural solutions for the migration of network functions to the cloud has been conducted, evaluating their advantages and disadvantages, as well as analysing the impact of SDN and NFV on network performance and scalability. Special attention is given to the distribution of network functions between the central cloud, peripheral computing nodes (MEC), and mobile infrastructure.

Results. The study identified key approaches to implementing Network Function Virtualisation (NFV) and Software-Defined Networking (SDN) in 5G mobile networks. The analysis of existing architectural solutions demonstrated that NFV reduces dependency on specialised hardware and enhances resource allocation flexibility, while SDN optimises network management through centralised control and load distribution.

Three primary strategies for network function migration in 5G were examined: full cloud migration, C-plane migration to the cloud, and a scenario-based approach. The advantages and disadvantages of each method were determined, along with their impact on network performance, latency, and scalability.

Conclusions. The study confirmed that the implementation of NFV and SDN in 5G networks enhances resource management efficiency, reduces capital and operational expenditures for network operators, and accelerates the deployment of new services. The analysis of existing solutions demonstrated that the adoption of distributed architectures, dynamic network management, and resource orchestration are key factors for the successful development of 5G.

Additionally, the article identifies the main challenges related to scalability, security, and the performance of SDN/NFV in mobile networks, which require further research.

Keywords: *5G; Network Function Virtualisation (NFV); Software-Defined Networking (SDN); network management; C-plane/U-plane; mobile infrastructure.*

INTRODUCTION

Currently, mobile electronic communication networks are experiencing a rapid increase in data traffic volume, driven by the widespread adoption of mobile applications and services with diverse quality of service (QoS) requirements (e.g., Netflix, YouTube, cloud gaming platforms). The fifth generation of mobile communication networks (5G) is designed to efficiently support such applications while unlocking new possibilities for the deployment of highly demanding services, including:

– Massive Machine Type Communications (mMTC): enabling large-scale data exchange among a vast number of IoT devices.
– Ultra-Reliable Low Latency Communications (UR-LLC): essential for mission-critical applications such as autonomous transportation, remote surgery, and industrial automation systems.

To achieve these goals, 5G networks leverage innovative technologies, including:

– Specialised radio interfaces, such as mmWave (millimetre waves), enabling ultra-high-speed connectivity.
– Heterogeneous Radio Access Networks (Heterogeneous RAN), integrating multiple access technologies for seamless connectivity.
– Hybrid coverage, utilizing both macro and micro cells to enhance network capacity.

– Network Function Virtualisation (NFV), ensuring flexible service deployment and scalable infrastructure.

Such innovations lead to a significant increase in network architecture complexity, as it must support diverse technologies with different protocol stacks and interfaces, often dependent on specific equipment vendors.

Managing such a complex network is impossible without the implementation of Software-Defined Networking (SDN), which plays a key role in ensuring the efficiency of 5G infrastructure. SDN enables the separation of the control plane (C-plane) from the user plane (U-plane) through standardised interfaces such as OpenFlow [1], allowing centralised traffic routing control and simplifying network administration.

Similar approaches are proposed for implementation in data centers and wired networks, where SDN ensures centralised management and adaptive configuration. In the field of mobile networks, research on SDN integration is actively being conducted for:

– Radio Access Networks (RAN) – adaptive spectrum management and dynamic resource allocation [2];
– Mobile Core Network – traffic optimisation and flexible routing control [3];
– Wireless networks not based on cellular technologies, such as Wi-Fi or LoRaWAN [4], [5].

The implementation of SDN concepts in mobile networks is becoming a critical factor for the efficient deployment of 5G, ensuring high performance and supporting future network technologies.

The purpose of this paper is to analyse approaches to Network Function Virtualisation (NFV) and Software-Defined Networking (SDN) in 5G networks, with a focus on their role in enhancing network manageability, scalability, and infrastructure efficiency. The study emphasizes architectural solutions for network function distribution, including:

– full cloud migration,
– control plane offloading to the cloud,
– hybrid approaches with dynamic load balancing.

Additionally, the paper explores SDN-based network management mechanisms, particularly the separation of control and user planes (C-plane/U-plane) and their impact on network performance and latency. The conducted analysis helps identify key challenges associated with SDN and NFV adoption and formulates scientifically grounded recommendations for their further development and integration into next-generation mobile networks.

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

Virtualisation and software-defined implementation of SDN in 5G systems have been the focus of numerous research studies. The findings of these studies highlight the advantages of virtualisation approaches in meeting the stringent requirements of 5G networks.

The proposed architectural approaches for building 5G networks can be categorized into three main groups, each defined by the placement of network functions.

Approach 1. Full-Cloud Migration Architecture. This solution involves placing all network functions in a cloud owned by the operator, which centrally manages all network functions and signalling processes (Fig. 1).

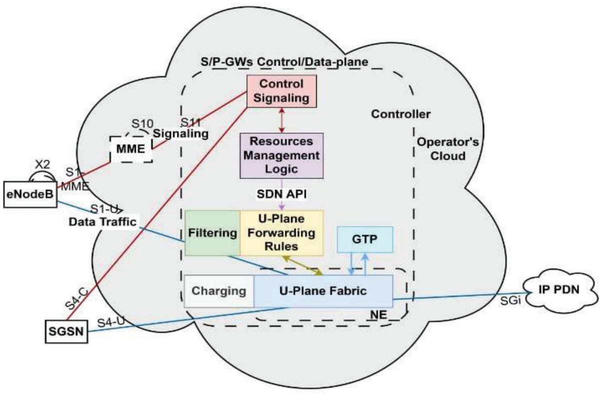

Fig.1. Full-Cloud Migration Architecture

Advantages of Full-Cloud Migration Architecture:

– High network availability due to centralised management.
– Easy integration and interoperability with other technologies and protocols that can be incorporated at the cloud level.
– Cost reduction, as there is no need for geographically distributed computing and storage resources.
– Simplified maintenance and updates while ensuring high computational performance and storage capacity.

This approach has been presented in studies [6], [7], [8].

The main idea of full-cloud migration is that all decisions regarding the management of the C-plane and U-plane are made centrally in the cloud environment. Additional architectural details were proposed in [9], where three levels of controllers are defined:

– Device Controller – responsible for access network selection.

- Edge Controller – handles authentication, security, access management, routing, and handovers.
- Orchestration Controller – manages network resources, including C-plane instantiation and U-plane load balancing.

Disadvantages of the full-cloud migration architecture:

- Cloud infrastructure performance limitations. Due to frequent C-plane operations and the large volume of U-traffic that must be processed at the PGW [7], the eNodeB-to-cloud connection can become a bottleneck. This leads to reliability issues, bandwidth constraints, and increased latency, which negates the advantages of this architecture.
- Limited flexibility. Since all mobile core functions are centralised in the cloud, this architecture only provides flexibility in creating different functional chains within the cloud. It does not support the distributed placement of network functions across the network, which restricts system adaptability

Approach 2. C-plane Cloud Migration Architecture. This architecture involves the separation of C-plane and U-plane functions, as discussed in [10]. According to Fig. 2, eNodeBs (or virtual-eNodeBs) are managed by a central cloud from a C-plane perspective, while U-traffic is routed through distributed U-plane nodes across the network, as illustrated in Fig. 2.

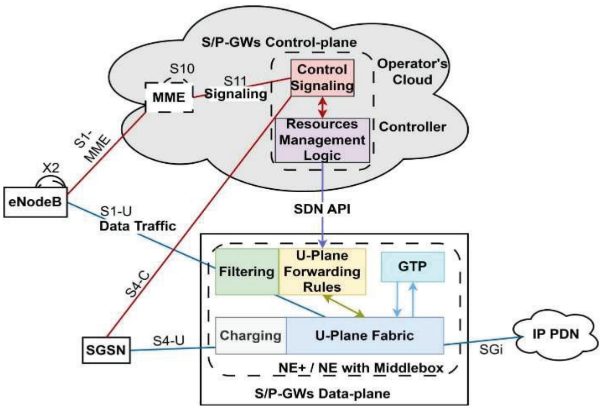

Fig. 2. C-plane Cloud Migration Architecture

Advantages of the C-plane Cloud Migration Architecture:

- Increased flexibility due to the ability to dynamically migrate virtualised U-plane components based on traffic load or service requirements [11].
- Reduction of the "bottleneck" effect that may arise from fully centralising the mobile core in the cloud.

However, this approach also has some drawbacks:

- The need to relocate critical functions (e.g., GTP tunnelling) to the U-plane to prevent all data packets from being forwarded through the cloud.
- It may require the use of specialised hardware (middleboxes) or provisioning of switching elements with programmable platforms capable of handling such functions.

Approach 3. Scenario-based Migration Architecture

The core idea of this approach is to deploy network functions both in the cloud and within the mobile infrastructure. Function migration occurs dynamically based on network congestion conditions and service requirements [12].

As shown in Fig. 3, some network functions can operate in edge clouds [13], enabling greater flexibility and scalability.

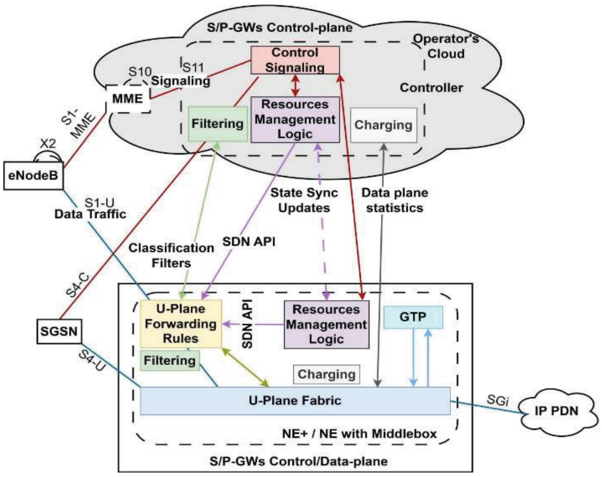

Fig. 3. Scenario-based Migration Architecture

This architecture enables the deployment of functions directly at the network edge for latency-sensitive services or scenarios that require additional functional capabilities (e.g., support for non-3GPP access points).

Examples of Research Studies: In [12], researchers analysed the benefits of relocating network functions within the mobile infrastructure and demonstrated that shifting functions closer to the radio access network can save up to 48% of network resources. In [14], a proposal was made to migrate charging functions to the cloud while exchanging statistical data with other mobile infrastructure components. Meanwhile, the study in [15] developed an optimal network function placement model that minimizes packet transmission costs.

Advantages of the Scenario-Based Migration Architecture:

- Rapid reconfiguration and increased resilience in case of network changes or failures due to support for a dynamic network topology.

- The ability to achieve ultra-low latency and optimise end-to-end connectivity.
- Support for large-scale device connectivity, which is a key factor for 5G networks.

Disadvantages of this Approach:

- The need for state synchronization between cloud networks and distributed elements of the mobile infrastructure, which may result in additional signalling overhead [14].
- When functions are migrated outside the central cloud, processing and storage performance limitations arise since the cloud architecture is not fully utilized.

VIRTUALISATION METHODS OF NETWORK FUNCTIONS (NFV) IN 5G

The evolution of 5G mobile networks is accompanied by increasing demands for flexibility, scalability, and cost-efficiency of the infrastructure. The implementation of Network Function Virtualisation (NFV) is one of the key strategies for optimising mobile operator networks, enabling the decoupling of network services from physical hardware. This approach allows network functions to be deployed as software modules that can dynamically change their deployment location based on current traffic loads and performance requirements.

1. Challenges of Traditional Mobile Network Architecture

The conventional architecture of operator networks relies on the use of specialised hardware components, such as routers, switches, EPC nodes, and RAN controllers. This approach leads to several critical challenges:

- High Capital Expenditures (CAPEX) and Operational Expenses (OPEX). Deploying new services requires purchasing and installing additional hardware, increasing the financial burden on operators.
- Long equipment lifecycle. Network hardware has a limited lifespan (typically 5–10 years), and its upgrade process demands substantial resources.
- Limited flexibility. Traditional network infrastructure follows a rigid structure, making it difficult to quickly introduce new services or scale resources in response to traffic fluctuations.
- Restricted automation capabilities. The absence of software-defined control mechanisms complicates the dynamic reconfiguration and optimisation of network operations.

2. Fundamentals of NFV and Its Role in 5G

The NFV (Network Function Virtualisation) concept aims to eliminate the aforementioned challenges by migrating network functions (such as EPC, SGW, PGW, HSS, and MME) into a software environment running on standard server hardware within virtualised environments (VMs, containers, or microservices).

NFV enables:

- Software-based implementation of network functions. Examples include virtual routers (vRouter), virtual base stations (vBTS), and virtual firewalls (vFirewall).
- Flexible service deployment management. Dynamic resource scaling based on traffic load ensures efficient utilization of computing power and optimises costs.
- Distributed infrastructure. NFV allows network functions to be deployed both in centralised data centers and at edge computing nodes (Mobile Edge Computing, MEC) [16].

3. NFV Architecture According to the ETSI Standard

The European Telecommunications Standards Institute (ETSI) has defined reference NFV architecture, which consists of four main layers (Fig. 4):

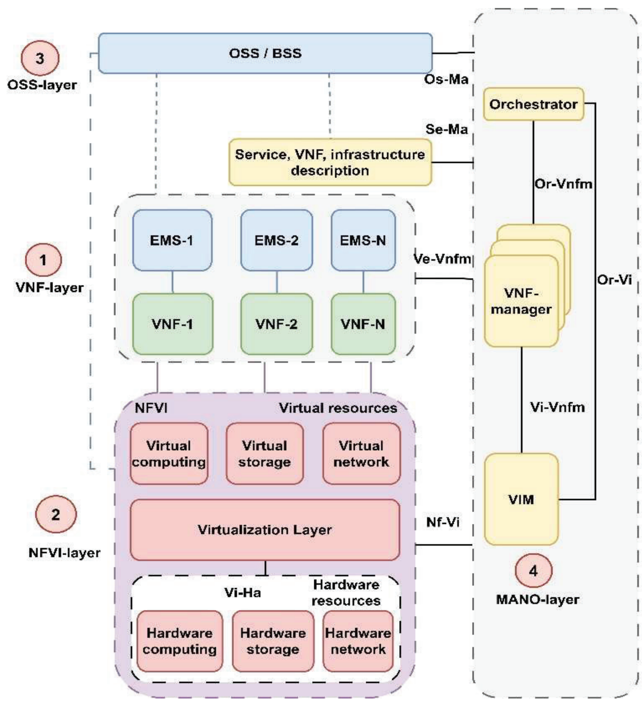

Fig. 4. Structure of NFV [16]

1. Virtualised Network Functions (VNF) Layer. This includes software-implemented network functions that operate within a virtualised environment (e.g., virtual EPC, virtual router, virtual NAT).
2. Infrastructure Layer (NFVI). Comprising hardware and software components that enable the execution of virtualised network functions. It includes:

- Physical resources: Servers, data storage, switches.
- Virtualisation layer: Ensures isolation and dynamic management of virtual machines and containers.

3. Operations Support System/Business Support System (OSS/BSS) Layer.

- Responsible for service management, subscriber database handling, and billing.

4. Management and Orchestration (MANO) Layer. It consists of three main components:

- NFV Orchestrator: Responsible for the creation, deployment, and removal of virtual functions in the network.
- Virtualised Infrastructure Manager (VIM): Manages resources in data centers and MEC nodes.
- VNF Manager: Oversees the lifecycle of each virtual function, including updates, monitoring, and scaling.

4. Advantages of NFV in 5G

The implementation of NFV in next-generation mobile networks offers several key benefits:

- Flexibility and Scalability. Enables the rapid deployment of new services without the need to upgrade physical infrastructure.
- Reduction in CAPEX and OPEX. Eliminating specialised hardware in favour of standard servers significantly reduces operator costs.
- Faster Service Deployment. Dynamic resource management allows operators to quickly adapt to market changes.
- Integration with Cloud and Edge Computing. Utilizing MEC and centralised cloud platforms enhances network performance and minimizes latency.
- Software-Defined Automation. NFV is closely integrated with SDN, providing centralised traffic management, route optimisation, and load balancing.

5. Challenges and Future Prospects

Despite its numerous advantages, the implementation of NFV in 5G networks presents several challenges:

- High Performance Requirements. Virtualisation of network functions can introduce latency, necessitating optimised traffic processing solutions such as hardware acceleration (e.g., DPDK).
- Security Assurance. As NFV relies heavily on cloud integration, new cybersecurity mechanisms are required to protect virtualised network environments.
- Complexity of VNF Lifecycle Management. Different operators adopt diverse NFV deployment strategies, making it essential to develop standardised frameworks and unified APIs for seamless integration.

FUTURE RESEARCH PROSPECTS

The previous sections have examined the role of SDN and virtualisation in 5G systems from various perspectives. This section identifies research areas that still require further investigation to ensure the efficient application of these technologies in 5G networks.

One of the key directions for future research is the optimal placement of network functions. Expanding upon the work in [14], [17], a well-developed cost model should incorporate target Quality of Service (QoS) requirements as input parameters, including:

- Throughput (channel capacity),
- Latency,
- Jitter,
- Network bandwidth,
- Response time, etc.

The challenges of VNF placement become more critical when considering the migration of network functions. In addition to the time required for deploying one or more virtual machines (VMs) to migrate one or multiple VNFs from one location to another, several key factors must be taken into account, such as security and integrity concerns within SDN/NFV environments [18], to determine the overall costs associated with function migration.

Furthermore, it is essential to consider that some User Equipment (UEs) may leverage U/C-plane separation or DUDe (Distributed User Data) mechanisms [19] to enhance their reliability and/or Quality of Service (QoS). This aspect complicates VNF migration due to the latency requirements of certain network functions, such as Hybrid Automatic Repeat Request (HARQ).

Such research should focus on analysing key aspects like latency, jitter, and overhead costs associated with communication between network functions. This is necessary to prevent excessive fragmentation of network functions, which could lead to increased delays and overhead traffic. Additionally, it is crucial to establish standardised APIs for communication between network functions to ensure their interoperability and seamless integration.

Another important yet underexplored aspect in the literature is the performance of SDN and NFV in 5G environments. While the significance of these paradigms for ensuring flexibility, customization, and reconfigurability is well established, there is still a lack of comprehensive understanding of how software-defined solutions can meet the stringent performance requirements of latency and reliability in 5G networks.

The degradation of performance when executing network functions as software-based solutions instead of dedicated hardware is a well-known issue.

This aspect must be adequately addressed in the design of 5G network architecture. Prior research [20], [21] has made initial progress in this area. However, further investigations are required to analyse realistic deployment scenarios and traffic loads, aiming to define key virtualisation parameters for 5G cloud platforms. These parameters include orchestrators, real-time hypervisors, optimised kernels, container memory allocation, and CPU resource management.

Another important research area focuses on the efficient integration of SDN within mobile network architectures and user devices. Studies such as [22], [23] identify SDN as a critical enabler for 5G and propose enhanced SDN controller functionalities, including mobility management and other advanced features. Further research is necessary to define optimal implementation strategies for these enhanced SDN capabilities.

CONCLUSION

The need for flexibility, reconfigurability, and customization in 5G mobile networks is driving vendors and operators to adopt novel approaches for network deployment. In this context, SDN and NFV virtualisation have emerged as key enabling technologies, as they decouple network functionality from underlying hardware, simplifying network management and upgrades.

This study provides a comprehensive overview of 5G mobile network virtualisation methods, analysing the evolution of network generations and the innovations introduced in comparison to previous technologies. This analysis allows for the identification of existing network functionalities and components currently implemented in cellular networks.

A detailed examination of the 5G ecosystem has been conducted, focusing on its applications and deployment scenarios. The study identifies the key architectural requirements imposed by 5G use cases, along with an evaluation of the limitations of 4G systems, which fail to fully meet these requirements. Based on this analysis, a set of essential architectural features for 5G is formulated, and the role of virtualisation in enabling these characteristics is clearly defined.

A comprehensive review of state-of-the-art research is presented, summarizing recent publications on the application of softwarization and virtualisation in the design and implementation of 5G network components and functionalities. Additionally, critical research areas requiring further investigation are outlined, guiding the scientific community toward the realization of a fully virtualised and software-defined 5G network architecture.

Thus, NFV and SDN are key research areas in modern telecommunications, enabling the development of flexible, scalable, and efficient networks. These advancements are particularly crucial in addressing the increasing demands for speed, reliability, and data processing capabilities in next-generation mobile systems.

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Сколець С.С.

Методи віртуалізації мобільних мереж 5g: архітектурні рішення та перспективи

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Проблематика. У статті досліджуються сучасні методи впровадження віртуалізації мережних функцій (NFV) та програмно-визначених мереж (SDN) у мобільних мережах п’ятого покоління (5G). Розглядається їхній вплив на побудову ефективної, гнучкої та масштабованої інфраструктури, а також аналізуються основні виклики, що виникають при їх впровадженні, та можливі перспективи подальшого розвитку.

Мета досліджень. Дане дослідження спрямоване на аналіз архітектурних рішень, що забезпечують ефективне відокремлення мережних функцій від фізичного обладнання, що, у свою чергу, сприяє автоматизованому управлінню ресурсами та оптимізації мережевої інфраструктури. Оцінено основні моделі реалізації віртуалізації у 5G, зокрема повну хмарну міграцію, перенесення C-площини до хмари та сценарний підхід до розподілу мережних функцій між мобільною та хмарною інфраструктурою.

У статті детально розглядаються принципи SDN, їх роль у поділі контрольної та користувацької площин (C-plane/U-plane), а також їхній вплив на продуктивність мережі, рівень затримок і можливості масштабування.

Проведено огляд сучасних досліджень щодо стандартів 5G, визначено напрями розвитку технологій NFV та SDN, а також виявлено ключові технічні та організаційні проблеми, що потребують подальшого опрацювання для підвищення ефективності мобільних мереж нового покоління.

Методика реалізацій. У роботі застосовано аналітичний метод дослідження, що включає систематизацію існуючих підходів до віртуалізації мережних функцій у 5G-мережах. Проведено порівняльний аналіз архітектурних рішень щодо міграції мережних функцій у хмару, оцінено їхні переваги та недоліки, а також проаналізовано вплив SDN та NFV на продуктивність та масштабованість мережі. Особливу увагу приділено вивченню розподілу мережевих функцій між центральною хмарою, периферійними обчислювальними вузлами (MEC) та мобільною інфраструктурою.

Результати досліджень. Аналіз існуючих архітектурних моделей показав, що застосування NFV дає змогу зменшити залежність від апаратного забезпечення та підвищити гнучкість управління ресурсами, а використання SDN забезпечує централізований контроль за мережею та оптимізацію розподілу навантаження.

Розглянуто три головні стратегії віртуалізації у 5G: повна хмарна міграція, перенесення C-площини до хмари та сценарний підхід. Проведено аналіз переваг і недоліків кожної з моделей, а також оцінено їхній вплив на продуктивність, затримки та загальну ефективність мережі.

Висновки. Впровадження SDN та NFV у мобільні мережі 5G сприяє підвищенню ефективності керування ресурсами, зменшенню фінансових витрат операторів та прискоренню розгортання нових сервісів. Аналіз сучасних підходів підтверджує, що використання розподіленої архітектури, гнучкої оркестрації ресурсів і динамічного керування мережею є ключовими факторами розвитку 5G.

Також визначено основні виклики, пов'язані з масштабованістю, безпекою та продуктивністю технологій SDN/NFV, що вимагають подальших досліджень та удосконалень.

Ключові слова: *5G; NFV; SDN; управління мережею; C-plane/U-plane; мобільна інфраструктура.*

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