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SDN and NFV: A Case Study and Role in 5G and Beyond

Abhishek Singh

abhishek.singh.geek@gmail.com

Abstract

Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are at the forefront of the technological revolution driving the evolution of 5G networks. These technologies decouple network functions from dedicated hardware, enabling a more flexible, scalable, and efficient network infrastructure. This paper delves into the architecture of SDN and NFV, elucidating their roles in enhancing the capabilities of 5G networks.[1] Through a detailed case study, we explore the practical applications and benefits of integrating SDN and NFV in a real-world 5G deployment, highlighting improvements in flexibility, cost efficiency, and network performance. The paper also addresses the challenges associated with implementing SDN and NFV, such as complexity, interoperability, and security concerns, and proposes solutions to mitigate these issues.[2] Looking ahead, we discuss future advancements that will further enhance the role of SDN and NFV in telecommunications. These include the integration of artificial intelligence (AI) and machine learning (ML) for smarter network management, the convergence with edge computing for ultra-low latency applications, and the development of network slicing to support diverse 5G use cases.[3]

By providing a comprehensive analysis of SDN and NFV, this research aims to offer valuable insights into their transformative impact on 5G networks and their potential to drive innovation and growth in the telecommunications industry beyond 5G. The findings underscore the importance of continuous advancements and collaboration among stakeholders to fully realize the benefits of these technologies.

Keywords: SDN, NFV, NFVI, MANO, 5G, URLCC, eMBB, mMTC, Performance

Introduction

The development of 5G networks has posed significant challenges for network operators, including the need for increased capacity, reduced latency, and improved reliability [4].

The telecommunications industry is experiencing a paradigm shift with the advent of 5G technology, which promises to deliver unprecedented speed, capacity, and connectivity. This transformation is driven by the need to support a wide range of applications, from enhanced mobile broadband (eMBB) and ultra-reliable low-latency communications (URLLC) to massive machine-type communications (mMTC). To realize the full potential of 5G, the underlying network infrastructure must be flexible, scalable, and efficient[5]. This is where Software-Defined Networking (SDN) and Network Function Virtualization (NFV) come into play.

Software-Defined Networking (SDN) is a revolutionary approach that decouples the control plane from the data plane, centralizing network control in a software-based controller. This separation allows for dynamic, programmable network management, enabling more efficient traffic handling and resource allocation. SDN provides the agility needed to adapt to changing network conditions and demands, making it an ideal solution for the dynamic environment of 5G networks.[6]

Network Function Virtualization (NFV) complements SDN by decoupling network functions from dedicated hardware appliances, running them as software on standard servers or cloud infrastructure. This virtualization of network functions allows for greater flexibility and scalability, as network services can be deployed, scaled, and managed more efficiently. NFV reduces the reliance on proprietary hardware, leading to cost savings and faster service deployment.[7]

The integration of SDN and NFV into 5G networks offers numerous benefits, including improved flexibility, resource efficiency, rapid deployment, cost efficiency, and enhanced network management. These technologies enable network operators to dynamically allocate resources, optimize performance, and quickly roll out new services, all while reducing capital and operational expenditures.[8]

However, the implementation of SDN and NFV also presents several challenges. The increased complexity of network architecture and management, the need for seamless interoperability between different components, and the introduction of new security vulnerabilities are some of the key issues that must be addressed. Advanced orchestration and automation tools, standardized interfaces and protocols, and robust security measures are essential to overcoming these challenges and ensuring the successful deployment of SDN and NFV in 5G networks.[9]

This paper aims to provide a comprehensive overview of SDN and NFV, exploring their architecture, benefits, and challenges. Through a detailed case study, we examine the practical applications and impact of these technologies in a real-world 5G network deployment. Additionally, we discuss future advancements that will further enhance the role of SDN and NFV in telecommunications, including the integration of artificial intelligence (AI) and machine learning (ML), the convergence with edge computing, the development of network slicing, and the use of blockchain technology.

SDN and NFV Architecture

Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are foundational technologies that enable the flexible, scalable, and efficient management of 5G networks. Their architectures are designed to decouple network functions from hardware, allowing for dynamic and programmable network management. Here, we delve into the detailed architecture of SDN and NFV and their integration into 5G networks.[10]

Software-Defined Networking (SDN) Architecture

SDN separates the control plane from the data plane, centralizing network control in a software-based controller. This separation allows for dynamic, programmable network management and more efficient traffic handling.

Key Components:

1. **SDN Controller**: The SDN controller is the central brain of the SDN architecture. It communicates with network devices using southbound APIs to instruct them on how to

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forward traffic. The controller provides a centralized view of the network, enabling dynamic and automated network management.[11]

2. **Southbound APIs**: These interfaces enable communication between the SDN controller and network devices. The most common southbound API is OpenFlow, which allows the controller to interact with switches and routers to manage traffic flows.[12]
3. **Northbound APIs**: These interfaces allow communication between the SDN controller and applications or orchestration systems. Northbound APIs enable the development of network applications that can programmatically control the network, such as traffic engineering, security policies, and network analytics.[13]

Architecture Layers:

- **Application Layer**: This layer consists of network applications that use the northbound APIs to interact with the SDN controller. These applications can include network monitoring, security, and traffic management tools.[14]
- **Control Layer**: The control layer is where the SDN controller resides. It manages the network by making decisions about how traffic should flow and communicating those decisions to the infrastructure layer.[15]
- **Infrastructure Layer**: This layer consists of the physical and virtual network devices (e.g., switches, routers) that forward traffic based on the instructions from the SDN controller.[16]

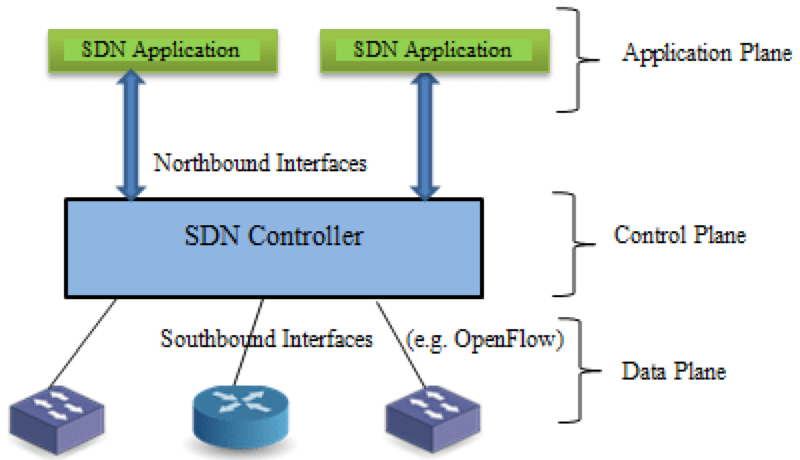

Fig1: Simplified SDN Architecture[36]

Network Function Virtualization (NFV) Architecture

NFV decouples network functions from dedicated hardware appliances, running them as software on standard servers or cloud infrastructure. This virtualization allows for greater flexibility and scalability, as network services can be deployed, scaled, and managed more efficiently.

Key Components:

1. **Virtualized Network Functions (VNFs)**: VNFs are software implementations of network functions that traditionally run on dedicated hardware. Examples include virtual firewalls, load balancers, and packet gateways. VNFs can be deployed on standard servers, reducing the need for specialized hardware.[17]
2. **NFV Infrastructure (NFVI)**: The NFVI provides the physical and virtual resources required to support the VNFs. This includes data centers, edge computing nodes, and cloud infrastructure. The NFVI consists of compute, storage, and networking resources that are virtualized to create a flexible and scalable environment for VNFs.[18]
3. **Virtualization Layer**: This layer includes hypervisors or containerization technologies that enable the deployment and management of VNFs on the NFVI. The virtualization layer abstracts the underlying hardware, allowing VNFs to run on any standard server.[19]

Architecture Layers:

- **VNF Layer**: This layer consists of the VNFs that provide the network functions. VNFs can be dynamically deployed, scaled, and managed based on network demands.[18]
- **NFVI Layer**: The NFVI layer includes the physical and virtual resources that support the VNFs. This layer provides the necessary infrastructure for hosting VNFs, including compute, storage, and networking resources.[20]
- **Management and Orchestration (MANO) Layer**: The MANO layer is responsible for the lifecycle management of VNFs, including their deployment, scaling, and monitoring. This layer includes the NFV Orchestrator, VNF Manager, and Virtualized Infrastructure Manager (VIM).[21]

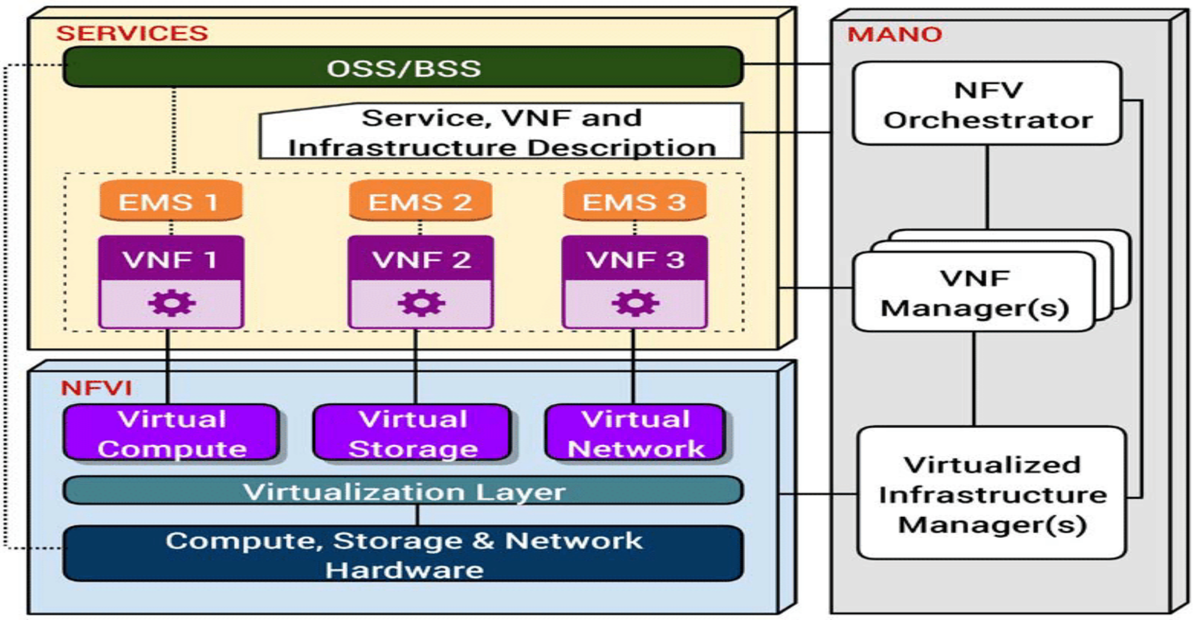

Fig 2: ETSI-NFV Architecture[37]

Integration of SDN and NFV in 5G Networks

The integration of SDN and NFV into 5G networks enables a more flexible, scalable, and efficient network infrastructure. By decoupling network functions from hardware and centralizing network control, SDN and NFV provide the agility needed to support the diverse and dynamic requirements of 5G applications.[10]

Key Integration Points:

1. **Dynamic Resource Allocation**: SDN and NFV enable dynamic allocation of network resources based on real-time demand. This flexibility is crucial for supporting the varying traffic patterns and workloads in 5G networks.[22]
2. **Network Slicing**: SDN and NFV are foundational technologies for network slicing, which allows the creation of multiple virtual networks on a shared physical infrastructure. Each slice can be customized to meet the specific requirements of different 5G use cases, such as eMBB, URLLC, and mMTC.[23]
3. **Edge Computing**: The convergence of SDN, NFV, and edge computing enables ultra-low latency applications by deploying VNFs at the network edge. This reduces latency and improves service quality for applications such as autonomous vehicles and remote surgery.[24]
4. **Enhanced Network Management**: The centralized control and programmability provided by SDN, combined with the flexibility of NFV, enable more efficient and automated network management. This improves overall network performance, reliability, and security.[25]

The architecture of SDN and NFV provides the foundation for the flexible, scalable, and efficient management of 5G networks. By decoupling network functions from hardware and centralizing network control, these technologies enable dynamic resource allocation, network slicing, edge computing, and enhanced network management. As 5G technology continues to evolve, the integration of SDN and NFV will be crucial for unlocking new capabilities and driving growth in the telecommunications industry.

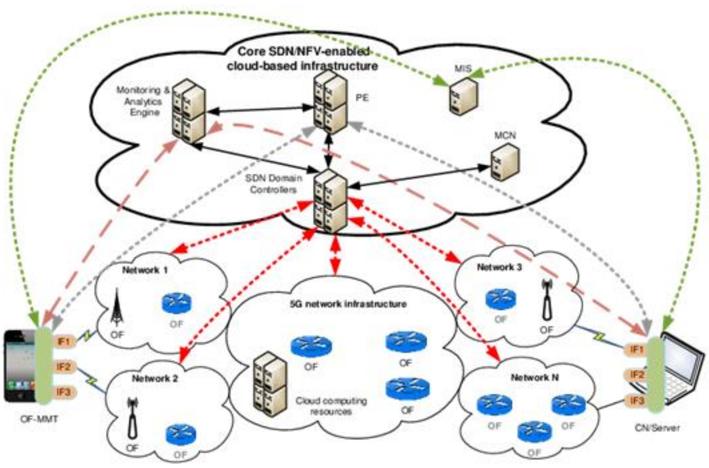

Fig 3: SDN/NFV-enabled network architecture[38]

Benefits of SDN and NFV in 5G Networks

The integration of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) into 5G networks offers numerous benefits that enhance the flexibility, scalability, and efficiency of network operations. These technologies are pivotal in realizing the full potential of 5G, supporting a wide range of applications and services.[26] Here are some of the key benefits:

1. **Flexibility and Scalability**
    - **Dynamic Resource Allocation**: SDN and NFV enable dynamic allocation of network resources based on real-time demand. This flexibility allows network operators to efficiently manage varying traffic loads and adapt to changing network conditions. For example, during peak usage times, resources can be dynamically scaled up to handle increased traffic and scaled down during off-peak times to conserve resources.
    - **Rapid Service Deployment**: Virtualized network functions (VNFs) can be instantiated and deployed more quickly than traditional hardware-based functions. This rapid deployment capability allows network operators to roll out new services and applications faster, meeting the evolving needs of users and businesses.
    - **Network Slicing**: SDN and NFV are foundational technologies for network slicing, which allows the creation of multiple virtual networks on a shared physical infrastructure. Each slice can be customized to meet the specific requirements of different 5G use cases, such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). This capability ensures that diverse applications receive the appropriate level of performance and resources.[27]
2. **Resource Efficiency**
    - **Optimized Resource Utilization**: By consolidating multiple network functions onto shared hardware, SDN and NFV optimize resource utilization. This reduces the need for dedicated appliances, leading to more efficient use of compute, storage, and networking resources. Network operators can achieve higher levels of efficiency and reduce the overall footprint of their network infrastructure.
    - **Cost Savings**: The shift from proprietary hardware to virtualized functions running on standard servers lowers capital expenditures (CAPEX) and operational expenditures (OPEX). Network operators can reduce the costs associated with purchasing, maintaining, and upgrading specialized hardware. Additionally, the ability to dynamically allocate resources based on demand further contributes to cost savings by minimizing over-provisioning.
3. **Enhanced Network Management**
    - **Centralized Control and Programmability**: SDN provides centralized control of the network through a software-based controller, enabling more efficient and automated network management. Network operators can programmatically control traffic flows, implement policies, and optimize network performance. This centralized control simplifies network operations and reduces the complexity of managing distributed network elements.[28]

- **Automation and Orchestration**: The integration of SDN and NFV enables advanced automation and orchestration capabilities. Network operators can automate routine tasks, such as provisioning, configuration, and monitoring, reducing the need for manual intervention. Orchestration tools can manage the lifecycle of VNFs, ensuring that network functions are deployed, scaled, and updated efficiently.
- **Improved Network Visibility**: SDN provides a centralized view of the network, allowing operators to monitor traffic flows, detect anomalies, and troubleshoot issues more effectively. Enhanced network visibility improves the ability to identify and resolve problems quickly, ensuring a high level of service quality and reliability.

4. **Quality of Service (QoS) and Performance**

- **Guaranteed QoS**: SDN and NFV enable the implementation of specific quality of service (QoS) parameters for different network slices. This ensures that each slice meets the performance requirements of its respective application. For example, a slice dedicated to URLLC can be configured to provide ultra-low latency and high reliability, while a slice for eMBB can be optimized for high data throughput.[29]
- **Low Latency and High Throughput**: The convergence of SDN, NFV, and edge computing allows network functions to be deployed closer to end-users, reducing latency and improving service quality. This is particularly important for latency-sensitive applications, such as autonomous vehicles, remote surgery, and real-time gaming. Additionally, the ability to dynamically allocate resources ensures that high-throughput applications receive the necessary bandwidth and processing power.[30]

5. **Innovation and Agility**

- **Support for Emerging Technologies**: SDN and NFV provide a flexible and programmable network infrastructure that can support emerging technologies and applications. This includes the Internet of Things (IoT), augmented reality (AR), virtual reality (VR), and smart cities. The ability to quickly deploy and scale network functions enables network operators to experiment with new services and business models, driving innovation and growth.[31]
- **Agile Network Operations**: The programmability and automation capabilities of SDN and NFV enable agile network operations. Network operators can quickly adapt to changing market demands, deploy new services, and respond to network events in real-time. This agility is essential for staying competitive in the fast-paced telecommunications industry.[32]

Case Study: SDN and NFV in a 5G Network Deployment

To illustrate the practical applications and impact of SDN and NFV, we examine a case study of a 5G network deployment by a leading telecommunications provider. This case study highlights the integration of SDN and NFV into the provider's network infrastructure, the challenges faced, and the benefits realized.

Background

The telecommunications provider aimed to deploy a 5G network capable of supporting diverse applications, including enhanced mobile broadband (eMBB), Internet of Things (IoT), and mission-critical services. The deployment required a flexible, scalable, and cost-efficient network infrastructure to meet the varying demands of these applications.[39]

SDN Integration:

- **Centralized Control**: The provider implemented an SDN controller to centralize network management and enable dynamic traffic routing. The SDN controller communicated with network devices using southbound APIs, such as OpenFlow, to manage traffic flows efficiently.
- **Programmability**: Northbound APIs allowed the integration of network applications and orchestration systems, enabling programmable network management. This programmability facilitated the implementation of advanced traffic engineering, security policies, and network analytics.

NFV Integration:

- **Virtualized Network Functions (VNFs)**: Key network functions, such as firewalls, load balancers, and packet gateways, were virtualized and deployed as VNFs on standard servers. This virtualization reduced the reliance on proprietary hardware and allowed for more flexible and scalable network management.
- **NFV Infrastructure (NFVI)**: The NFVI included data centers and edge computing nodes to support low-latency applications. The virtualization layer, consisting of hypervisors and containerization technologies, enabled the deployment and management of VNFs on the NFVI.

Results

The integration of SDN and NFV into the 5G network deployment yielded several significant benefits:

a. **Improved Flexibility**: The provider could dynamically allocate resources and scale network functions based on real-time demand. This flexibility ensured optimal performance for different applications, such as high-speed internet access for eMBB and low-latency communication for mission-critical services.
b. **Cost Savings**: The shift from proprietary hardware to virtualized functions on standard servers resulted in substantial cost savings. The provider reduced capital expenditures (CAPEX) by minimizing the need for specialized hardware and operational expenditures (OPEX) by streamlining network management.
c. **Faster Service Deployment**: Virtualized functions enabled quicker deployment and updates, allowing the provider to roll out new services rapidly. This agility was crucial for staying competitive in the fast-paced telecommunications industry.

d. **Enhanced Network Performance**: Centralized control and programmability improved network efficiency and reliability. The provider could implement advanced traffic engineering and security policies, resulting in a better user experience and higher service quality.

e. **Support for Diverse Applications**: The flexible and scalable network infrastructure supported a wide range of 5G applications, from IoT devices to high-bandwidth video streaming. Network slicing allowed the provider to create customized virtual networks for different use cases, ensuring that each application received the appropriate level of performance and resources.

Challenges and Solutions

While the deployment was successful, the provider faced several challenges:

- **Complexity**: The integration of SDN and NFV added complexity to the network architecture and management. To address this, the provider implemented advanced orchestration and automation tools to simplify management and reduce operational complexity.
- **Interoperability**: Ensuring seamless interoperability between different VNFs and SDN components was critical. The provider adopted standardized interfaces and protocols to enhance compatibility and integration.
- **Security**: Virtualized environments introduced new security vulnerabilities. The provider implemented robust security measures, such as encryption, access control, and continuous monitoring, to mitigate risks and protect the network.

Findings

- The case study demonstrates that the integration of SDN and NFV into a 5G network deployment can significantly enhance flexibility, scalability, cost efficiency, and network performance. Key findings include:
- **Dynamic Resource Allocation**: SDN and NFV enable dynamic allocation of network resources, ensuring optimal performance for diverse applications and use cases.
- **Cost Efficiency**: Virtualizing network functions on standard servers reduces CAPEX and OPEX, leading to substantial cost savings.
- **Enhanced Network Management**: Centralized control and programmability improve network efficiency, reliability, and security.
- **Support for Diverse Applications**: The flexible and scalable network infrastructure supports a wide range of 5G applications, ensuring that each application receives the appropriate level of performance and resources
- **Increased network capacity and performance**: Through the virtualization of network functions, the operator could dynamically allocate resources based on demand, ensuring that the network could handle the surge in 5G traffic without costly and time-consuming hardware upgrades. [33]

- **Rapid service deployment:** The ability to instantiate virtual network functions on-demand allowed the operator to quickly roll out new 5G services, reducing the time-to-market and enabling them to stay competitive.
- **Improved operational efficiency:** The centralized control and programmability of the SDN architecture enabled the operator to automate network management tasks, reducing operating expenses and improving overall network efficiency.
- **Enhanced network resilience:** The decoupling of network functions from hardware through NFV provided the operator with improved fault tolerance and the ability to quickly recover from network failures, ensuring reliable 5G service delivery.
- **Improved network programmability:** The separation of control and data planes in SDN allowed the operator to centrally manage and configure the network, enabling rapid service deployment and optimization.

The deployment of the SDN and NFV-enabled 5G network was a complex undertaking, requiring extensive planning, integration, and optimization. Extensive testing and validation were conducted to ensure the seamless interoperability of the various components, as well as to assess the network's performance, scalability, and security. The operator worked closely with technology vendors and partners to ensure seamless interoperability between the various components of the solution. [33]

Future Advancements and Growth

As 5G technology continues to evolve, future advancements in SDN and NFV will be essential for unlocking new capabilities and applications. Key areas of development include: [4][32]

- **Multi-domain Orchestration:** Integrating SDN and NFV across multiple network domains, including access, backhaul, and core, to enable end-to-end network optimization and service delivery [4].
- **Edge Computing Integration:** Combining SDN, NFV, and edge computing to support low-latency, high-bandwidth applications at the network edge, such as autonomous vehicles, AR/VR, and industrial IoT.
- **Artificial Intelligence and Machine Learning:** Leveraging AI/ML for intelligent network management, automation, and optimization, enabling self-configuring, self-healing, and self-optimizing networks.
- **5G Network Slicing:** Enhancing network slicing capabilities to provide customized, on-demand virtual networks for diverse 5G use cases, ensuring optimal performance and resource utilization.
- **Network Programmability and APIs:** Enhancing network programmability through open APIs and software platforms, allowing for rapid development and deployment of new network services and applications.

- **Blockchain Technology:** Integrating blockchain technology with SDN and NFV to enable secure, decentralized network management and resource allocation, especially in multi-tenant environments.

The successful integration of SDN and NFV into 5G networks demonstrates their critical role in enabling the flexible, scalable, and cost-effective network infrastructure required to support the diverse and demanding applications of the future.

Conclusion

SDN and NFV are transformative technologies that play a pivotal role in the evolution of 5G networks and beyond. By enabling flexible, scalable, and cost-efficient network management, these technologies support the diverse and demanding applications required for the next generation of telecommunications.[40]

The integration of SDN and NFV allows network operators to dynamically allocate resources, improve operational efficiency, and provide enhanced reliability and security. SDN separates the control and data planes, enabling centralized management and programmability, while NFV decouples network functions from dedicated hardware, enabling on-demand deployment and scaling. Together, these technologies enable network operators to quickly adapt to changing market needs, rapidly deploy new services, and optimize network performance.[41]

As the telecommunications landscape continues to evolve, future advancements in SDN and NFV will be crucial for unlocking new capabilities, improving network performance, and driving growth in 5G and future cellular networks. Key areas of development include multi-domain orchestration, edge computing integration, the use of artificial intelligence and machine learning for network optimization, enhanced 5G network slicing, and the integration of blockchain technology for secure, decentralized network management.[42]

The successful integration of SDN and NFV into 5G networks demonstrates their critical role in enabling the flexible, scalable, and cost-effective network infrastructure required to support the diverse and demanding applications of the future. As the telecommunications industry continues to evolve, the continued advancement and adoption of these transformative technologies will be essential for network operators to stay agile, responsive, and competitive in the dynamic market landscape.[34] As we look towards the future, the integration of **AI-driven network management** will be crucial. AI and machine learning can enhance network automation, predict potential issues, and optimize resource allocation in real-time, leading to more resilient and efficient networks. The convergence of **SDN, NFV, and edge computing** will enable ultra-low latency applications, such as autonomous vehicles and remote surgery, by bringing processing power closer to the data source.

Network slicing, enabled by SDN and NFV, will allow the creation of multiple virtual networks on a shared infrastructure, each tailored to specific use cases with distinct performance requirements. This capability is vital for supporting the diverse range of 5G applications, from enhanced mobile broadband to ultra-reliable low-latency communications and massive machine-type communications.

Moreover, the adoption of **blockchain technology** for decentralized and tamper-proof network management can enhance security and trust in SDN and NFV deployments. Blockchain can ensure data integrity and prevent unauthorized access, which is particularly important in large-scale and distributed network environments.

Finally, **enhanced collaboration** between telecommunications providers, technology vendors, and standards organizations will drive innovation and ensure the development of interoperable solutions. Such collaboration is essential for creating standardized protocols and frameworks that facilitate the seamless integration and deployment of SDN and NFV technologies.

In conclusion, SDN and NFV are transformative technologies that play a critical role in the evolution of 5G networks and beyond. By enabling flexible, scalable, and cost-efficient network management, these technologies support the diverse and demanding applications of 5G. As the telecommunications landscape continues to evolve, future advancements in SDN and NFV will be essential for unlocking new capabilities and driving growth, paving the way for the next generation of network innovations.[35]

References

[1] I. F. Akyildiz, S. Nie, S. Lin, and M. Chandrasekaran, “5G roadmap: 10 key enabling technologies,” Jun. 19, 2016, Elsevier BV. doi: 10.1016/j.comnet.2016.06.010.

[2] P. Iovanna and F. Ubaldi, “SDN solutions for 5G transport networks,” Sep. 01, 2015. doi: 10.1109/ps.2015.7329032.

[3] V. P. Kafle, Y. Fukushima, P. Martínez-Julia, and T. Miyazawa, “Consideration On Automation of 5G Network Slicing with Machine Learning,” Nov. 01, 2018. doi: 10.23919/itu-wt.2018.8597639.

[4] F. Z. Yousaf, M. Bredel, S. Schaller, and F. Schneider, “NFV and SDN—Key Technology Enablers for 5G Networks,” Oct. 06, 2017, Institute of Electrical and Electronics Engineers. doi: 10.1109/jsac.2017.2760418.

[5] C. Sexton, N. J. Kaminski, J. M. Márquez-Barja, N. Marchetti, and L. A. DaSilva, “5G: Adaptable Networks Enabled by Versatile Radio Access Technologies,” Jan. 01, 2017, Institute of Electrical and Electronics Engineers. doi: 10.1109/comst.2017.2652495.

[6] D. Kreutz, F. M. V. Ramos, P. Veríssimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, “Software-Defined Networking: A Comprehensive Survey,” Jan. 01, 2014, Cornell University. doi: 10.48550/arXiv.1406.

[7] B. Han, V. Gopalakrishnan, L. Ji, and S. Lee, “Network function virtualization: Challenges and opportunities for innovations,” Feb. 01, 2015, Institute of Electrical and Electronics Engineers. doi: 10.1109/mcom.2015.7045396.

[8] L. B. Le et al., “Enabling 5G mobile wireless technologies,” Sep. 26, 2015, Springer Nature. doi: 10.1186/s13638-015-0452-9.

[9] F. Reynaud, F.-X. Aguessy, O. Bettan, M. Bouet, and V. Conan, “Attacks against Network Functions Virtualization and Software-Defined Networking: State-of-the-art,” Jun. 01, 2016. doi: 10.1109/netsoft.2016.7502487.

[10] J. Zhang, W. Xie, and F. Yang, “An Architecture for 5G Mobile Network Based on SDN and NFV,” Jan. 01, 2015. doi: 10.1049/cp.2015.0918.

[11] S. Singh and R. K. Jha, "A Survey on Software Defined Networking: Architecture for Next Generation Network," Sep. 16, 2016, Springer Science+Business Media. doi: 10.1007/s10922-016-9393-9.

[12] D. E. Comer and A. Rastegarnia, "OSDF: A framework for software defined network programming," Jan. 01, 2018. doi: 10.1109/ccnc.2018.8319173.

[13] W. Zhou, L. Li, M. Luo, and W. Chou, "REST API Design Patterns for SDN Northbound API," May 01, 2014. doi: 10.1109/waina.2014.153.

[14] S. G. Du, J. W. Lee, and K. Kim, "Proposal of GRPC as a New Northbound API for Application Layer Communication Efficiency in SDN," Jan. 05, 2018. doi: 10.1145/3164541.3164563.

[15] P. Porras, S. W. Cheung, M. Fong, K. Skinner, and V. Yegneswaran, "Securing the Software Defined Network Control Layer," Jan. 01, 2015. doi: 10.14722/ndss.2015.23222.

[16] S. Denazis, J. H. Salim, D. Meyer, and O. Koufopavlou, "Software-Defined Networking (SDN): Layers and Architecture Terminology," Jan. 2015. doi: 10.17487/rfc7426.

[17] R. Mijumbi, J. Serrat, J. Gorricho, N. Bouten, F. D. Turck, and R. Boutaba, "Network Function Virtualization: State-of-the-Art and Research Challenges," Sep. 04, 2015, Institute of Electrical and Electronics Engineers. doi: 10.1109/comst.2015.2477041.

[18] D. Rajan, "Common Platform Architecture for Network Function Virtualization Deployments," Mar. 01, 2016. doi: 10.1109/mobilecloud.2016.10.

[19] B. Yi, X. Wang, K. Li, S. K. Das, and M. Huang, "A comprehensive survey of Network Function Virtualization," Jan. 31, 2018, Elsevier BV. doi: 10.1016/j.comnet.2018.01.021.

[20] C. Tipantuña and P. Yanchapaxi, "Network functions virtualization: An overview and open-source projects," Oct. 01, 2017. doi: 10.1109/etcm.2017.8247541.

[21] R. Riggio, S. N. Khan, T. Subramanya, I. G. B. Yahia, and D. López, "LightMANO: Converging NFV and SDN at the edges of the network," Apr. 01, 2018. doi: 10.1109/noms.2018.8406266.

[22] G. Nencioni, R. G. Garroppo, A. J. Gonzalez, B. E. Helvik, and G. Procissi, "Orchestration and Control in Software-Defined 5G Networks: Research Challenges," Jan. 01, 2018, Wiley. doi: 10.1155/2018/6923867.

[23] Y. Khettab, M. Bagaa, D. L. C. Dutra, T. Taleb, and N. Toumi, "Virtual security as a service for 5G verticals," Apr. 01, 2018. doi: 10.1109/wcnc.2018.8377298.

[24] R. Ford, A. Sridharan, R. Margolies, R. Jana, and S. Rangan, "Provisioning Low Latency, Resilient Mobile Edge Clouds for 5G," Jan. 01, 2017, Cornell University. doi: 10.48550/arxiv.1703.10915.

[25] M. Feng, S. Mao, and T. Jiang, "Enhancing the performance of futurewireless networks with software-defined networking," Jul. 01, 2016, Springer Science+Business Media. doi: 10.1631/fitee.1500336.

[26] C. Tsirakis, P. Matzoros, and G. Agapiou, “State-of-the-art on Virtualization and Software Defined Networking for Efficient Resource Allocation on Multi-tenant 5G Networks,” Jan. 01, 2017, EDP Sciences. doi: 10.1051/matecconf/201712503009.

[27] Q. He et al., “Network Slicing to Enable Resilience and High Availability in 5G Mobile Telecommunications,” Jan. 01, 2018, EDP Sciences. doi: 10.1051/matecconf/201824603028.

[28] J. Moysen and L. Giupponi, “From 4G to 5G: Self-organized Network Management meets Machine Learning,” Jan. 01, 2017, Cornell University. doi: 10.48550/arXiv.1707.

[29] S. Seetharaman and D. Krishnaswamy, “A programmable and adaptive framework for 5G Network Slicing,” Sep. 01, 2019. doi: 10.1109/5gwf.2019.8911704.

[30] M. A. Lema et al., “Business Case and Technology Analysis for 5G Low Latency Applications,” Jan. 01, 2017, Cornell University. doi: 10.48550/arxiv.1703.09434.

[31] E. Crisostomi, R. Shorten, and F. Wirth, “Smart Cities: A Golden Age for Control Theory? [Industry Perspective],” Sep. 01, 2016, Institute of Electrical and Electronics Engineers. doi: 10.1109/mts.2016.2592782.

[32] W. Lee and H. Kim, “Deployment Scenario and Architecture of MANO for NFV Network Services,” Dec. 01, 2016. doi: 10.1109/icissec.2016.7885848.

[33] S. Vassilaras*et al.*, "The Algorithmic Aspects of Network Slicing," *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 112-119, Aug. 2017.

[34] B. Li, B. Cheng, M. Wang, M. Niu, and J. Chen, “A Lightweight Network Slicing Orchestration Architecture (poster),” Jun. 12, 2019. doi: 10.1145/3307334.3328643.

[35] R. Casellas, R. Muñoz, R. Vilalta, and R. Martí-nez, “Orchestration of IT/cloud and networks: From Inter-DC interconnection to SDN/NFV 5G services,” May 01, 2016. doi: 10.1109/ondm.2016.7494060.

[36] S. Mittal, “Performance Evaluation of Openflow SDN Controllers,” in *Proceedings of the International Conference on Advances in Computing and Communication Engineering*, Springer, Singapore, 2018, pp. 785–793

[37] J. Gil-Herrera and J. Botero, “Resource Allocation in NFV: A Comprehensive Survey,” *IEEE Trans. Netw. Serv. Manag.*, vol. 13, no. 3, pp. 394-407, Sept. 2016

[38] M. Kantor, R. State, T. Engel, and G. Ormazabal, “A policy-based per-flow mobility management system design,” *Proc. ACM SIGCOMM Comput. Commun. Rev.*, vol. 45, no. 4, pp. 35–42, Oct. 2015.

[39] Aptira, "Case Study - Telecommunications NFV," *Aptira*, 2016. [Online]. Available: https://aptira.com/wp-content/uploads/2016/10/aptira_casestudy_TelecommunicationsNFV_02.pdf.

[40] M. Chiosi, D. Clarke, P. Willis, A. Reid, J. Feger, and M. Bugenhagen, "Network Functions Virtualisation: An Introduction, Benefits, Enablers, Challenges & Call for Action," in *SDN and OpenFlow World Congress*, 2012.

[41] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Communications Magazine*, vol. 51, no. 2, pp. 114-119, Feb. 2013.

[42] A. Gudipati, D. Perry, L. E. Li, and S. Katti, "SoftRAN: Software Defined Radio Access Network," in *Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking*, Hong Kong, China, 2013, pp. 25-30.