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APPLICATION OF SOFTWARE-DEFINED NETWORKING AND NETWORK FUNCTIONS VIRTUALIZATION TECHNOLOGIES IN THE 5G TRANSPORT NETWORK

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ABSTRACT

The paper analyzes the architectural foundations of applying Software-Defined Networking (SDN) and Network Functions Virtualization (NFV) in the transport segment of 5G mobile networks. Based on a comparative analysis of international standards (3GPP, ETSI, IETF, ITU) and the research literature, traditional and SDN-based transport networks are compared , and a hierarchical model for placing virtualized functions is described together with the requirements it imposes on the transport network. Network slicing technologies are classified by isolation level, granularity, set-up time and resource efficiency. According to operator and vendor data, SDN orchestration shortens service life-cycle operations by a factor of 18–240, with the largest gains in device configuration and QoS changes. Existing approaches to adaptive control are shown to be developing in isolation, which justifies a comprehensive closed-loop control architecture.

1. Introduction

The development of the digital economy, in particular, the tasks set out in the "Digital Uzbekistan – 2030" strategy [1] require the rapid introduction of modern mobile communication networks, primarily 5G networks. According to the requirements of IMT-2020, the 5G network must support three classes of services - mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC), and machine-to-machine mass communication (mMTC) [2]. The steady growth of mobile traffic [3] and the service-oriented architecture of the 5G core [4] impose new requirements on the transport network in terms of throughput, latency, synchronization, and flexibility [5]. In traditional transport networks, the control logic is distributed across each device, and configuration is performed manually. This approach does not allow for rapid service provision and timely response to load changes in the 5G environment, where network functions are dynamically deployed and relocated. Therefore, the transition to software-defined transport network management is an urgent scientific and practical issue.

Literature review. The concept of software-defined networks (SDN) was formed as a result of the Clean Slate project at Stanford University and the University of California, Berkeley, and the work of N. McKeown, S. Schenker, and M. Casado [6–8]. Among the open SDN controllers, the ONOS platform with a cluster architecture has been developed for operator networks [9]. Network functions virtualization (NFV) has been standardized by ETSI [10], and network partitioning is described in detail in 3GPP and IETF documents and comments [11–13]. Mechanisms for constructing transport partitions based on segment routing and the IGP flexible algorithm (Flex-Algo) [14–17], and the ACTN architecture for hierarchical management of multi-domain networks [18] have been proposed. There are also studies on dynamic traffic management systems (B4, SWAN) [19, 20] and the application of machine learning to network modeling [21, 22]. However, these works usually consider SDN, NFV , and partitioning separately; it is not enough to analyze them holistically from the perspective of adaptive control of the 5G transport network.

The purpose of the research is to systematically analyze the architectural foundations of the application of SDN and NFV technologies in the 5G transport network and identify gaps in existing adaptive control approaches.

To achieve the goal, the following tasks were set:

1. traditional and SDN transport networks and assessment of the impact on service lifecycle operation time.
2. the deployment hierarchy of 5G virtualized functions and its requirements for the transport network.
3. Classification of transport section implementation technologies by isolation level.
4. Describe the process of creating a multi-domain management and section.
5. Analyze adaptive management approaches and identify their limitations.

2. Materials and methods

The research is of a theoretical-analytical nature, and the following groups of sources served as its material:

Standards and recommendations: 3GPP (TS 23.501, TS 28.530), ETSI GS NFV 002, ITU-R and ITU-T recommendations, OIF FlexE agreement [2, 4, 5, 10, 11, 23].

IETF documents (RFC): segment routing, Flex-Algo, transport slices, ACTN, PCEP, NETCONF, YANG, BFD [13–18, 24–26, 28].

Scientific publications: Scientific papers and reviews on SDN, P4, ONOS, partitioning, traffic control , and machine learning [6–9, 12, 19–22, 27, 29].

Industry data: reports from operators and equipment manufacturers [3].

The following methods were used in the study:

1. **Systematic analysis** – breaking down SDN and NFV reference architectures into layers, interfaces, and functional blocks.
2. **Comparative analysis** - comparison of traditional and SDN transport networks in terms of control logic location, network vision, route selection, configuration, service provisioning time, and other criteria.
3. **Classification** - grouping transport segment implementation technologies by isolation level, granularity, creation time , and resource efficiency.
4. **Summarization –** aggregation of time estimates for service lifecycle operations (design, configuration, testing, activation, changing QoS parameters) from operator and manufacturer reports. Efficiency was calculated as the ratio of execution times for each operation in the traditional and SDN network.
5. **Modeling and diagramming** – depicting the hierarchy of function placement, partitioning into slices, traffic segmentation using Flex-Algo, and the sequence of slice creation in the form of graphical models.

3. Results

3.1. Comparative analysis of SDN architecture and traditional network

The main idea of the SDN concept is to separate the control plane, which makes decisions about how to handle traffic, from the data plane, which directly transmits packets [6, 7]. The control plane is logically abstracted from network devices to a centralized software controller that manages many devices through an open, standardized interface. The Open Networking Foundation (ONF) defines SDN technology through four principles: separation of control and data planes; logical centralization of management; open interfaces between planes; and the ability to program the network by external applications. The standard three-layer architecture of SDN technology is shown in Figure 1.

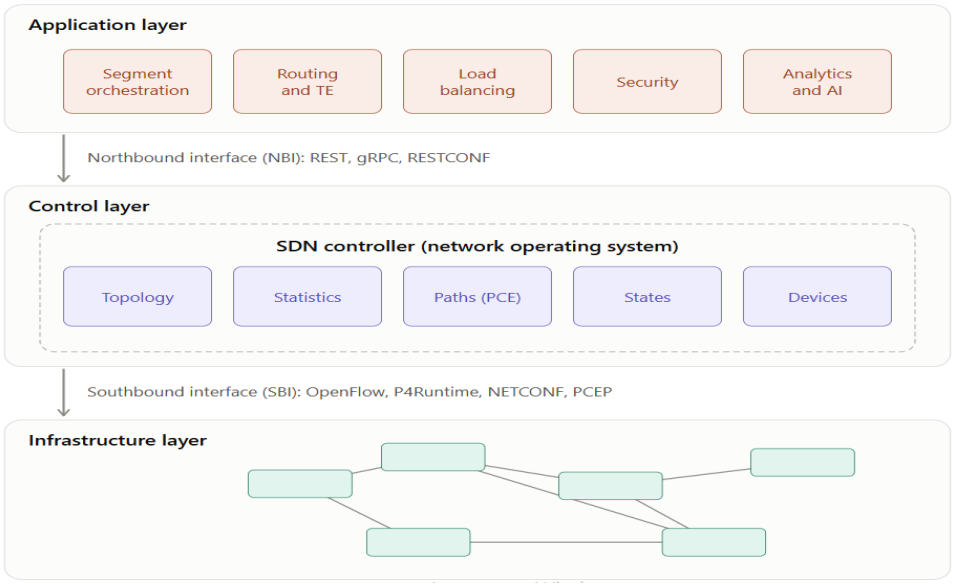


Figure 1. Three-layer architecture of a software-configurable network

The infrastructure layer is made up of network devices - switches and routers. In a pure SDN model, they only forward packets according to the rules set by the controller. In practice, a hybrid model is used in operator transport networks: the devices maintain distributed protocols (IS-IS, BGP) for basic connectivity, and the controller only performs path optimization and service management.

The management layer is represented by the SDN controller. It is a network operating system that maintains a global view of the network (topology, channel state, flow tables), provides basic services (topology detection, statistics collection, route calculation, device management) , and abstracts network complexity for applications. The ONOS controller, with its cluster architecture, extensive set of southbound protocols , and intent framework, is one of the most suitable open platforms for operator transport networks [9].

The application layer contains applications that implement network logic such as routing and traffic management, load balancing, security, segment orchestration, and analytics. Interaction with the controller is achieved through a northbound interface (NBI), typically based on REST, gRPC, or RESTCONF with YANG data models [26].

The controller interacts with devices via the South-West Interface (SBI). In addition to the historically first OpenFlow protocol [6], NETCONF/YANG (configuration) [25, 26], PCEP (route management) [24], BGP-LS (topology collection), gNMI (streaming telemetry) , and P4Runtime (pipeline programming) [27] are widely used in operator transport networks. East-west interfaces are used for interaction between different domain controllers or cluster instances. The results of a comparative analysis of traditional and software-driven approaches are presented in Table 1.

Table 1. Comparison of traditional and software-driven transport networks

Criterion	Traditional network	SDN network
Location of control logic	Distributed on each device	Logically centralized in the controller
Network vision	Local (LSDB database of neighbors)	Global (topology, load, SLA)
Route selection	Shortest path by static metric	Optimization by optional criteria
Configuration	Manually via the CLI interface of each device	Programmatically, via API, by intents
Service provision time	Days - weeks	Minutes – hours
Response to load changes	Not available or manual	Automatic
Manufacturer Dependency	High (custom OS)	Reduced (open interfaces)
Innovations	Determined by the manufacturer	Determined by the operator (applications)
Risks	Local faults	Controller failure or overload

The effectiveness of implementing SDN technology is primarily manifested in the reduction of operation times. Figure 2 presents the estimated execution times for the main operations of the service life cycle, summarized from operator and manufacturer reports.

Source: aggregated estimates from operator and manufacturer reports

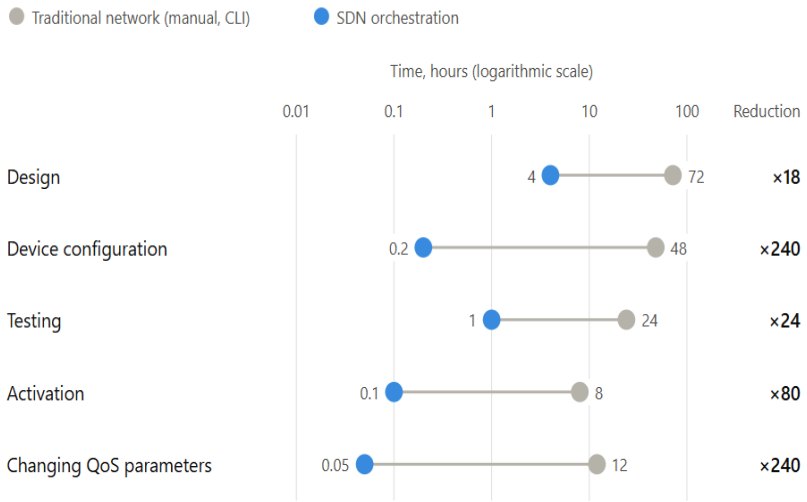


Figure 2. Time to complete service lifecycle operations in a traditional network and an SDN network

The greatest improvement (up to 240 times in two to three orders of magnitude) is observed in the stages of configuring devices and changing QoS parameters, since in SDN technology they are performed completely automatically. The smallest reduction is observed in the design stage, which requires human participation - 18 times .

3.2. NFV and virtualized functions deployment hierarchy

The concept of Network Functions Virtualization (NFV) was proposed by a group of leading telecommunications operators within the framework of ETSI [10]. Its essence is to move network functions (routers, inter-network screens, mobile network core functions) from specialized equipment to standard servers in the form of virtual network functions (VNF) or container functions (CNF). SDN and NFV are complementary concepts: NFV virtualizes the functions of nodes, while SDN programs the communication between them.

The ETSI NFV reference architecture [10] (Figure 3) includes three main blocks. The NFVI infrastructure integrates physical compute, memory , and network resources and a virtualization layer (KVM hypervisor or Kubernetes container platform). The VNF virtual network functions run on top of the NFVI under the control of element management systems (EMs). The NFV MANO management and orchestration block includes the NFVO orchestrator that manages network services and resources, the VNFM manager that manages the VNF lifecycle (creation, scaling, patching, and deletion), and the VIM virtualized infrastructure manager (e.g., OpenStack) that manages NFVI resources.

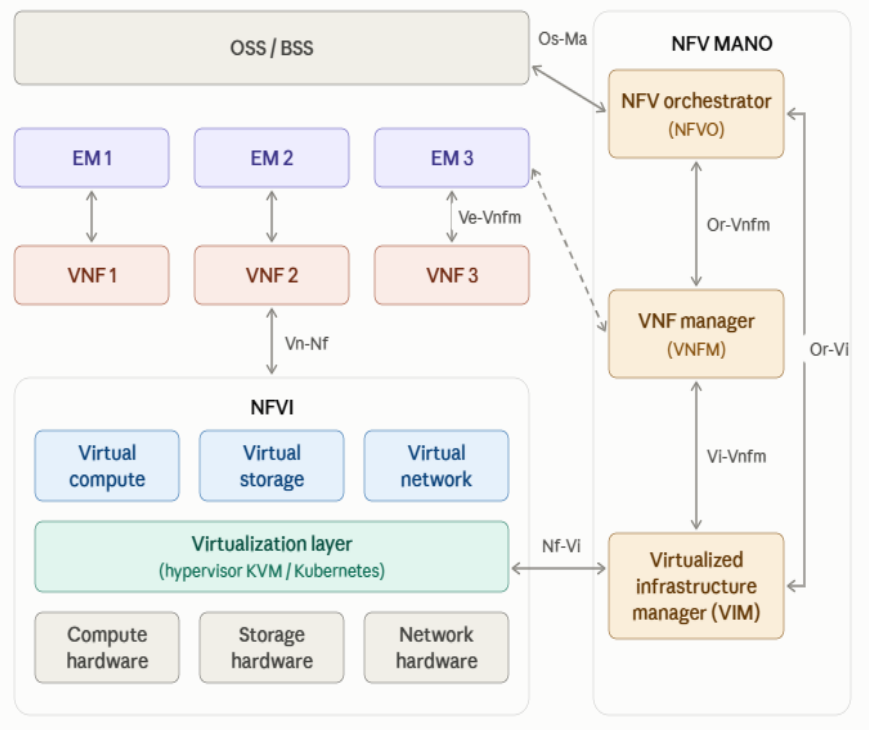


Figure 3. ETSI NFV MANO reference architecture

The analysis showed three implications of NFV for the 5G transport network. First, core functions (UPF, SMF, AMF) and CU can be dynamically deployed and scaled in distributed data centers (MIBM); this means that the transport network should be able to quickly reconfigure the connection when the location of the functions changes. Second, the SDN controller itself and the analytics modules are implemented as cloud applications that can be deployed with MANO tools. Third, the transport network functions themselves (vPE virtual routers, inter-network screens, SecGW security gateways) can also be virtualized.

The deployment of virtualized functions of the 5G network follows a hierarchical principle (Figure 4). The core control plane functions, OSS/BSS systems, orchestrators, and SDN controllers are deployed in a small number of central MIBMs (1–3 per country) where economies of scale are maximized; latency to the subscriber is 20–50 ms. For eMBB traffic, UPF, CU-CP, and analytics systems are deployed in regional MIBMs (5–15); latency is 5–10 ms. For URLLC traffic and edge computing (MEC) applications, UPF and CU-UP are deployed in edge nodes 1–5 ms from the subscriber. Only DU, RU , and fronthaul (TSN) switches remain in the access areas ; latency is less than 1 ms.

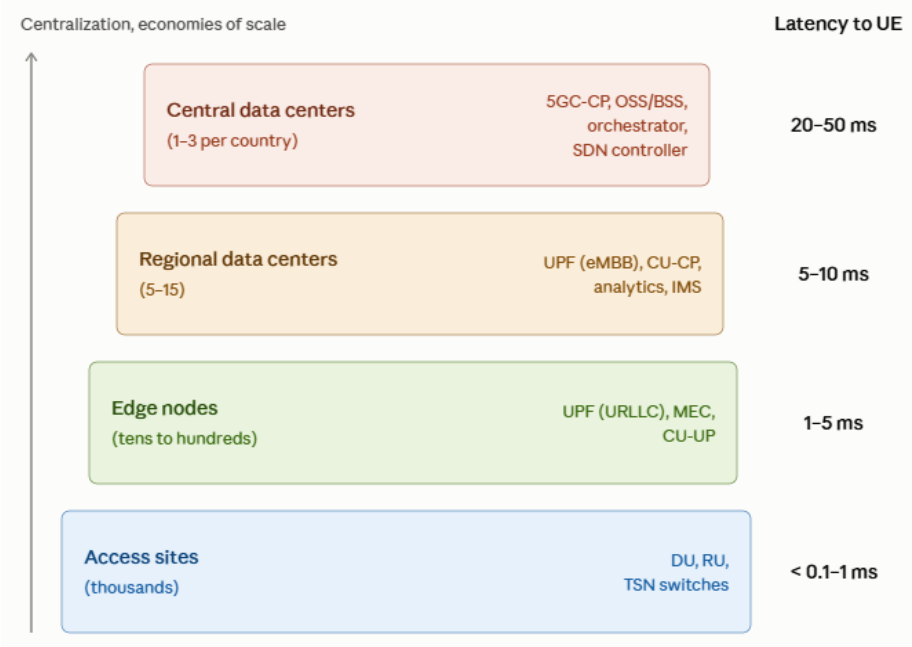


Figure 4. 5G network virtualized function deployment hierarchy and end-to-end latency

Such a hierarchy imposes two sets of requirements on the transport network. First, the traffic between the layers of the hierarchy has different characteristics: between access points and edge nodes - fronthaul/midhaul traffic with strict requirements for latency; between edge and regional nodes - aggregated N3/N9 user traffic; between regional and central MIBMs - mainly signaling and control traffic. Second, when scaling or migrating a virtualized function (for example, when

moving a UPF copy to another edge node due to overload), the transport network must reorganize the connection in a time comparable to the migration itself, that is, in seconds. This can only be achieved with software management integrated with the NFV MANO system through the northern interface of the SDN controller.

In recent years, virtual machines have been supplanted by container network functions (CNFs) running on Kubernetes. Containers are launched in seconds, making scaling more dynamic. CNFs use data plane acceleration technologies such as DPDK (user-space packet processing), SR-IOV (direct access of virtual functions to the network adapter), and SmartNIC/DPU (hardware offload) to provide high-performance packet processing. As a result, an operator implementing a 5G cloud core inevitably faces the need to coordinate the management of computing resources and the transport network.

3.3. Dividing the transport network into sections

Network slicing is a key architectural concept of 5G that allows the creation of multiple isolated "three-by-three" logical networks with the same characteristics as the shared physical infrastructure. 3GPP defines a slice as a logical network that provides specific network capabilities and characteristics [4, 11, 12]. The S-NSSAI slice identifier consists of the SST type (8 bits) and the SD differentiator (24 bits). The standardized values of the SST and their requirements for the transport segment are listed in Table 2.

Table 2. Standardized types of sections (STS) and requirements for the transport segment

SST	Type	Basic services	Transportation requirements
1	eMBB	4K/8K video, AR/VR, FWA	High bandwidth, latency 5–10 ms
2	URLLC	Industrial automation, V2X, energy	Delay ≤ 1–5 ms, losses ≤ 10^{-5}, protection transition < 50 ms
3	MIoT (mMTC)	Sensors, counters, trackers	Large number of sessions, low speed
4	V2X	Vehicle communication	Low latency, high mobility
5	HMTC	High-performance machine-to-machine communication	Deterministic delay
6	HDLLC	High-speed communication with low latency	High speed and low latency at the same time

The three-to-three slice consists of a radio access network (RAN), a transport network , and a core subnetwork (Figure 5). The slice management is hierarchical: the NSMF function manages the three-to-three slice and divides it into subnetworks, each of which is managed by

its own NSSMF function. The TN-NSSMF role for the transport segment is performed by the transport network orchestrator in conjunction with the SDN controller. In the IETF, a transport slice (IETF Network Slice, RFC 9543) [13] is described by a set of connection points (SDP) and service level objectives (SLO): guaranteed bandwidth, maximum delay, jitter, loss ratio, availability.

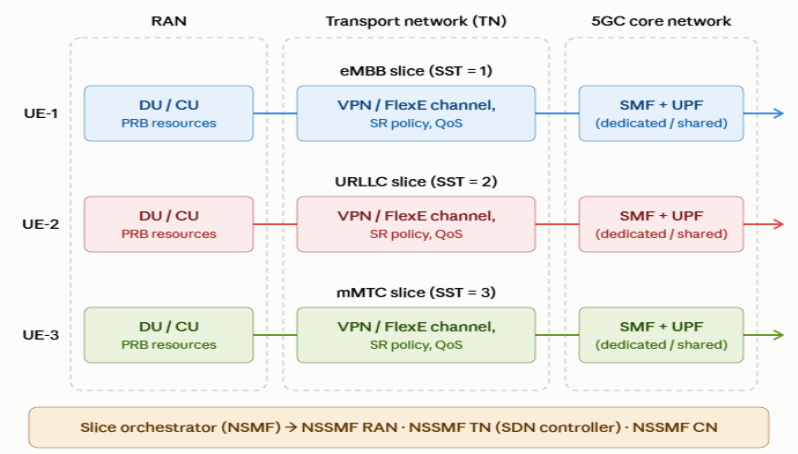


Figure 5. Dividing a 5G network into three-by-three segments: RAN, transport network , and core segments.

Transport segmentation can provide different levels of isolation (Table 3). “Soft” isolation is achieved through QoS mechanisms and virtual private networks (L2VPN/L3VPN, EVPN) over shared channels. “Hard” isolation is achieved by allocating physical resources – FlexE slots [23], ODUflex channels or wavelengths. An intermediate option is segment routing with flexible algorithms (Flex-Algo) and separated policy [16, 17], in which segment traffic is routed along a separate logical topology with its own metric (e.g., delay).

Table 3. Technologies for implementing transport sections and the level of insulation

Technology	Insulation level	Granularity	Creation time	Resource efficiency
DiffServ QoS + VPN	Soft	Traffic classes	Seconds	High
SR Policy / Flex-Algo	Soft+ (separate paths)	Flow/Topology	Seconds	High
VLAN + TSN (802.1Qbv)	Medium (time windows)	Queues	Seconds	Medium
FlexE-channel	Definitely	5 Gbps (1 Gbps on FlexE	Seconds – minutes	Medium

Technology	Insulation level	Granularity	Creation time	Resource efficiency
		2.x)		
ODUflex (OTN)	Definitely	1.25 Gbps	Minutes	Medium
Wavelength (WDM)	Physicist	10–400 Gbps	Minutes – hours	Low

Table 3 shows that as the isolation level increases, the time to create a section increases and the resource utilization efficiency decreases. Therefore, the selection of section technology should be based on a trade-off between isolation and efficiency.

3.4. Segmentation of traffic using Flex-Algo

An effective mechanism for "soft" segmentation in segment-routed networks is the IGP flexible algorithm (Flex-Algo, RFC 9350) [14]. It allows defining several logical topologies on a single physical network; each of them uses its own metrics (administrative, delay, TE value) and its own restrictions (exclusion of channels of a certain color, for example, satellite or radio-relay link channels). Each algorithm is associated with its own set of prefix SIDs , and segment traffic is routed along the shortest routes in "its" topology without the need to explicitly specify the route.

An example of the Flex-Algo implementation is shown in Figure 6. For eMBB traffic, Algorithm 128 with IGP administrative metric is used, which selects a path along the upper chain of nodes with high-speed channels. For URLLC traffic, Algorithm 129 with dynamically measurable (RFC 8570) [15] delay metric is used , and the path is taken along the lower chain with the lowest total delay. Both algorithms operate simultaneously in the same network, and changes in channel delay lead to automatic recalculation of URLLC paths.

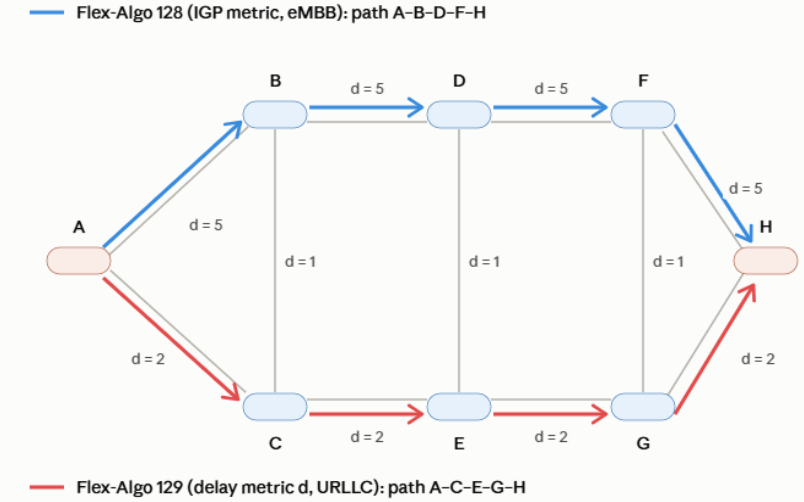


Figure 6. Segmentation of traffic using Flex-Algo flexible routing algorithms

The disadvantage of Flex-Algo is that the paths are still calculated in a distributed manner, according to the shortest route, without taking into account the channel load and the total requirements of the flows. Therefore, it is advisable to use Flex-Algo as a basic mechanism for separating topologies, and on top of it, the SDN controller sets specific SR-policies [17] for the flows that require optimization.

3.5. The process of creating a multi-domain management and transport layer

The operator's transport network is typically multi-domain and multi-layered: it includes an IP/MPLS-SRv6 packet domain, an OTN/WDM optical domain, and a fronthaul domain; the domains may be built on equipment from different manufacturers. To manage such networks, the IETF has developed the ACTN (Abstraction and Control of TE Networks, RFC 8453) architecture [18] (Figure 7).

The ACTN architecture includes three layers of controllers. The Customer Network Controller (CNC) represents the service requirements – for 5G networks, its role is performed by the slice orchestrator. The Multi-Domain Service Coordinator (MDSC) performs three-to-three route computation (hierarchical PCE), domain coordination , and resource abstraction in the form of virtual networks (VN). The Provisioning Controllers (PNC) manage individual domains. The CMI and MPI interfaces use YANG data models (TE-topology, TE-tunnel, VN, TE-service-mapping), which ensures multi-vendor compatibility.

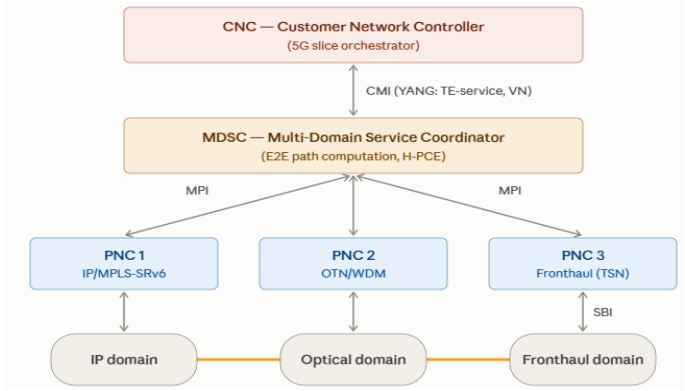


Figure 7. Hierarchical architecture of ACTN transport network management

The process of creating a transport slice in a hierarchical control system is illustrated in the sequence diagram (Figure 8). A slice request with SLA parameters (bandwidth B, delay D, jitter J, availability A) from the NSMF block arrives at the TN-NSSMF block, which is translated into a request for creating a virtual network and TE tunnels. The SDN controller contacts the PCE block to calculate the restricted routes, obtains the explicit route (ERO) or SID list , and sets SR policies on the PE nodes via NETCONF or PCEP [24, 25]. After validation and SLA compliance, the slice is activated and the S-NSSAI identifier is returned to the NSMF block. During the operation phase, the nodes continuously transmit telemetry; based on it, the controller generates KPI reports and performs adaptation if necessary.

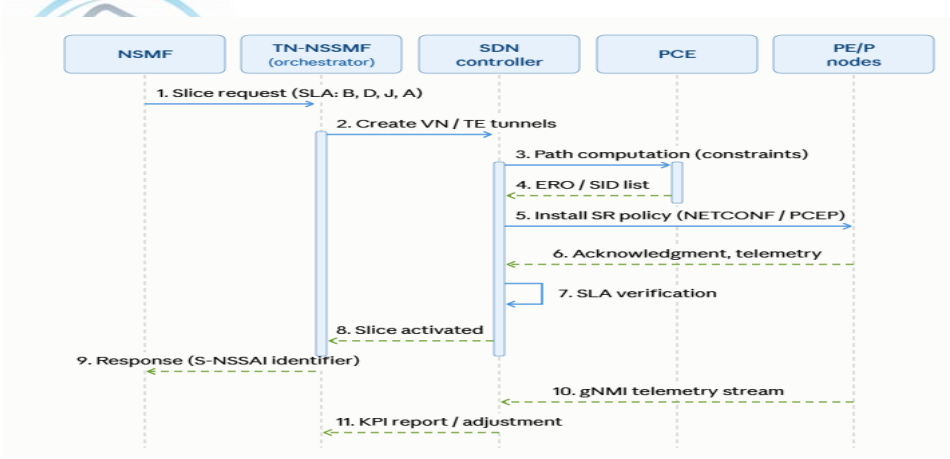


Figure 8. Flowchart for creating a transport section

4. Discussion

The results confirm the need to transition to software-defined control of the 5G transport network in three ways. First, SDN orchestration reduces the time of service lifecycle operations from 18 times (design) to 240 times (configuration, changing QoS parameters); the greatest gain is achieved in two to three orders of magnitude and is observed precisely in the automated stages. Second, the scaling of NFV/CNF functions within seconds also requires the reconfiguration of the transport link in the same time interval, which cannot be achieved with manual configuration. Third, slicing technologies require a compromise between isolation and resource efficiency, which requires centralized management that dynamically allocates resources between slices.

A literature review showed that adaptive control in SDN networks has been researched in four main areas (Table 4).

Table 4. Adaptive control directions in SDN networks and their limitations

Direction	Methods and examples	Result achieved	Restrictions
Dynamic Traffic Management (DT)	Periodic solution of multi-product flow problem; Google B4, Microsoft SWAN [19, 20]	Channel load up to 90–100%	Designed for elastic traffic, latency requirements are not taken into account; period is in the order of minutes
Machine learning	ARIMA, Holt–Winters, LSTM, GRU; GNN	Traffic forecasting, delay estimation	Long learning, low interpretability, no guarantee of

Direction	Methods and examples	Result achieved	Restrictions
	(RouteNet); DRL [21, 22]		compliance with restrictions
Quick protection	OpenFlow FAST-FAILOVER, TI-LFA, BFD [28]	Reconnect in tens of milliseconds	Backup roads do not take into account loading and section requirements
Energy-efficient management	Disable channels and line cards during off-peak hours	Energy consumption is reduced by 20–40% during night hours	Forecasting is necessary to activate resources on time

The main problem with machine learning-based approaches for URLLC segments, especially DRL, is that they do not guarantee that latency and reliability constraints are met. B4 and SWAN systems, while achieving high throughput, are not designed for latency-sensitive traffic. Fast protection and energy-saving mechanisms impose conflicting requirements: one requires spare resources, the other seeks to turn off redundant resources.

Thus, the listed directions are mainly developing separately from each other. There is no comprehensive solution that combines load forecasting, delay-constrained routing, resource allocation between sections with different levels of isolation, fast protection taking into account the load, and energy saving in a single circuit. A promising direction is to build such a solution on the basis of the “observe - analyze - plan - execute” closed control loop of autonomous systems [29], using Flex-Algo as the basic topological separation mechanism, and the SDN controller as an optimizing link through SR-policies.

Research limitations. The time estimates in Figure 2 are summarized from operator and manufacturer reports and are not direct measurements of the author; they may vary depending on the network size, level of automation, and organizational processes. Quantitative evaluation of the effectiveness of the proposed complex architecture using simulation modeling or a test bench (e.g., based on Mininet and ONOS) is a task for further research.

5. Conclusion

Based on the analysis conducted, the following conclusions were drawn:

1. of control and data planes and the logical centralization of management, provides a global view of the network and its programmability. This is a prerequisite for adaptive management of 5G traffic, reducing the time of service lifecycle operations by 18-240 times .

2. its cluster architecture, extensive set of southbound protocols , and intent framework, is the most suitable open platform for building an adaptive controller for an operator's transport network.

3. The hierarchical model of virtualized function deployment (central, regional MIBM, edge and access nodes) requires the transport network to service traffic of different characteristics between layers and reorganize the connection in seconds, which is achieved through the integration of SDN and NFV MANO.

4. Transport network partitioning can be implemented with varying degrees of isolation, from soft (QoS, SR-policies, Flex-Algo) to hard (FlexE, ODUflex, WDM) ; as isolation increases, creation time increases and resource utilization efficiency decreases. The ACTN hierarchical architecture provides three-to-three management of a multi-domain network.

5. justifies the need to develop a comprehensive architecture with a closed control loop that combines prediction, constrained routing, resource allocation between segments, rapid protection , and energy conservation.

can be used in the design and modernization of 5G transport networks of Uzbek communication operators , as well as in further scientific research.

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