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Estimating the Overhead of Flow Control in Hierarchical Software-Defined Networks

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Abstract:

Software-defined networks of a large dimension have a complex and branched structure; they are inherent in them by continuous expansion and dynamic characteristics, which significantly limits the application of known methods for their modelling and optimization. Consequently, the problems of the analysis of next-generation networks at the system level and the study of their new features, mainly due to large size and complex geometry (topology), are relevant. The tasks of constructing optimal structures of complex networks are solved by means of the theory of hierarchical systems, which is widely used to describe network structures, in particular, flow control networks. The work is devoted to the load balancing in SDN depending on their topological hierarchical structure and type of traffic (vertical, horizontal, and hybrid).

Keywords:

architecture network, fractal topology, hierarchical system, hybrid traffic, scalability, software-defined network

1. Introduction

In the field of telecommunication technologies, there is a steady tendency to unite and integrate networks using different network technologies and different information transmission medium. This led to the emergence of a new class of networks – next-generation (NG) wireless networks [1] that use a single communication network with a developed radio access system and a support for user mobility. Wireless networks allow the organization of local (LAN) and city networks (MAN), easily integrated into WANs.

Given that wireless networks form the basis of the real Internet, it can be predicted that for a long time, such networks will be inherent in the Future Networks, and the problems associated with their reliability, productivity, Quality of Service (QoS), security and scalability will be further enhanced.

The ways of solving these problems are in the area of efficient management of network resources, which involves solving three groups of tasks. The synthesis of the

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topological structure of the network, taking into account its development, flow dynamics and reliability, the choice of performance indicators and algorithms for the functioning of its elements [2, 3]; realization of technology of interaction (system of information exchange protocols, having a multi-level structure) [4, 5]; and managing interoperability at the transport level [6-8] (developing switching, routing, flow management, network reconfiguration, etc.).

That is why, recently, researchers and IT-engineers have focused on researching of the network management methods and network virtualization tools, and developing approaches to the use of distributed data, which has become de facto the main areas of the architecture of the Future Internet.

Analysis of the processes of designing and operating computer networks suggests that their reliability and performance to a large scale depends on the topology [9]. This means that effective solutions for managing networks with one topology sometimes become unsuitable for networks with another topology. Therefore, the task of balancing traffic in them, which involves the redistribution of flows through the existing backup paths in the network bypassing overloaded segments, is solved by logical rearrangement of the primary network topology [10]. The most known and successful solution for creation of networks with the changing topology is Software-Defined Networking (SDN) technology [11-13], which has allowed to get rid of the static architecture of traditional and relatively slow IP networks, with their decentralized and complex management principle, and to centralize network monitoring in a single network component, separating the process forwarding information packets from the routing process.

The basic principles of SDN architecture implemented in the OpenFlow protocol [11] are as follows: programmability, abstraction from forwarding, centralized management, dynamic configuration, open standards and independence from manufacturers. According to IT analysts, most of the distributed IT companies have more than six network or security devices, each with its own unique interface for deployment and remote management. These devices include Ethernet switches, Wi-Fi controllers, routers, WAN optimizers, SD-WANs, IP VPNs, firewalls, intrusion prevention and intrusion detection systems, and more others.

Achievements in network virtualization enable to combine a wide range of network functions (SD-WAN, routing, network security, Wi-Fi and LAN) on a single platform that is easy to deploy and to manage [12].

The main problems [13] encountered during the deployment and operation of networks are divided into traffic management problems, the transmission of WAN information and associated WAN service providers, and security and compatibility with other WAN elements.

In order to generate new revenue, network operators, in addition to traditional requirements for service quality, will need to take into account security requirements, user location and application location – either in the data centre [14] or in the cloud [15]. This is because geographically distributed organizations typically support two or more types of WANs for their work. The most common are MPLS connection, broadband Internet access and 5G technology. To do this, most network operators need to use outdated Border Gateway Protocols next to the new ones to facilitate the management of MPLS channels.

Communication channels such as Ethernet, DSL, or wired connections range from one third to half the cost of MPLS channels at the appropriate data rates. Internet access also has a number of benefits of broad availability and speed of provision of resources over MPLS. Most operators are beginning to use the hybrid WAN architecture [4], i.e.

MPLS connection – for critical traffic, and Internet connectivity – for high-speed access to cloud or SaaS applications, email, transfer and save files, video applications.

This will allow to achieve full availability, to increase bandwidth and to reduce costs and increase the productivity of applications in general.

If most of the Internet problems SDN are solved [16, 17], scalability remains one of the bottlenecks in this architecture, and there is practically no information about the successful technical solutions in this area. It should be noted that the problem of scalability is particularly acute for operators of networks for large cities, especially in Smart City projects.

As a result of the development of the theory of complex networks [9, 10], it was possible to develop SDN control methods taking into account such topological properties of large-dimensional networks as self-similarity and large-scale invariance.

These topological properties are associated with a special class of physical processes – fractal processes. Therefore, special attention is given to the tasks of developing constructive methods for the analysis and synthesis of fractal topologies [10, 18] and their influence on the nature of the formation of control signals in the functioning of networks of large dimension [17].

Thus, the proliferation of network technology standards [19], the variety of equipment and media, the increase in the traffic and its proportion of inelasticity, the general tendency to increase the size of networks, the ability to support excessive communication channels and the introduction of SDN technology, have created prerequisites for optimizing their structure and developing a new architecture of the Future Internet.

The main goal of the study is to develop the virtualization technology of the architecture of the Future Internet and to manage it in fundamentally new scale-invariant computer networks, taking into account the principle of hierarchical control.

2. Material and Methods

The architecture of the Future Internet must take into account the fact that the intensity of the information flow of data varies in the network in different ways [13, 20-24]. An increase in the intensity of information flows in such networks leads to the occurrence of overloads of communication channels, which affects the delay in the transmission of information and even its loss. In this case, the distribution of subscriber density uniquely determines the intensity of the information flow.

In order to achieve the required level of service quality in networks regarding the speed and reliability of the transmission of information, it should be foreseen that most modern networks have a multi-level, hierarchical, structural organization. Increasing the number of levels simplifies the tasks of building and scaling nets, but at the same time it worsens their time characteristics.

In general, the task of ensuring the connectivity of the network of subscriber nodes and the efficient management of information flows between them in networks (Fig. 1a) is solved by constructing a backbone network of routers (Fig. 1b).

The assessment of such a management structure is reduced to the solution of the task of constructing a hierarchical management system for subscriber nodes. Namely, it is necessary to distribute a plurality of initial (user) nodes on routers of the backbone level.

The conducted analysis of the principles of construction and functioning of networks allowed to introduce a multilevel hierarchical structure of the network, whose model is shown in Fig. 2.

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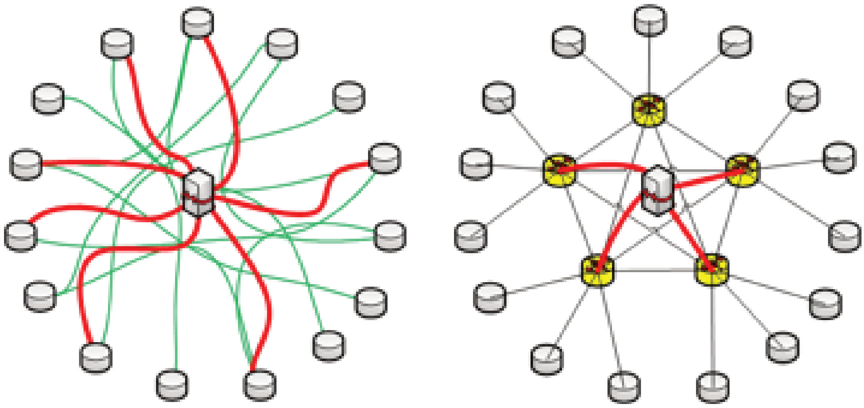

a) *b)*

Fig. 1 Description of the task of structuring the network: a) logical flows between the nodes and the gateway; b) a structured network using routers

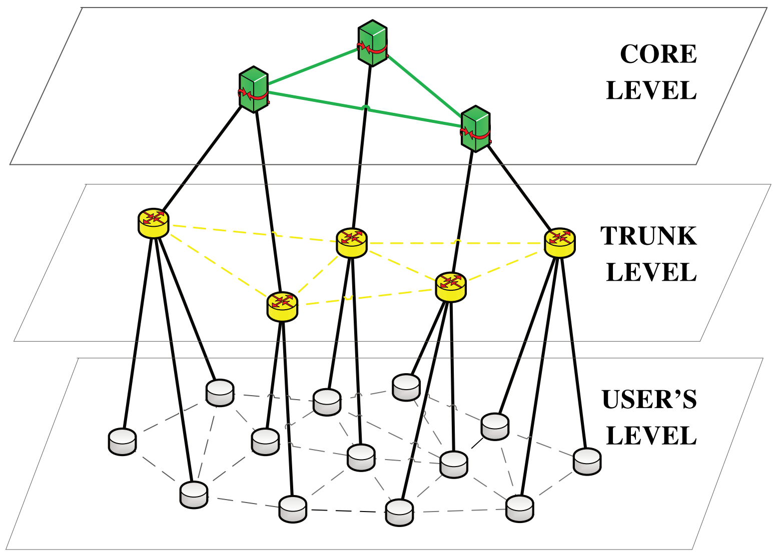

Fig. 2 Classical network architecture

According to this delineation of network levels, to synthesize the structure of the network H it is necessary:

- to construct a bound oriented graph $R = \langle W, E_R \rangle$ with multiple vertices (user nodes) W and multiple edges (physical connections between user nodes) $E_R \subseteq W \times W$,
- to build a complete network structure H on the basis of the link graph and the input flow matrix, where: (w – the source node, w' – the destination node) through available incident vertices (routers) m of the backbone M
  $H : G(V, E)$,

where G is an oriented graph with a set of vertices $V \subseteq W \cup M$ and a set of edges E. If $W \supseteq V$, for each flow between w and w' which is not connected to the same m, G has a directional path from w to w' through M,

- to determine the optimal H^* junction of trunk nodes that minimizes the additive flow control cost function $c(m, H)$:

$$H^* = \operatorname{Arg} \min_{H \in \Omega} \sum_{m \in M} c\left[f_H(m), H \right] \tag{1}$$

where $f_H(m)$ – the total flow through the node m.

Thus, the requirements for efficient management of resources in Future Networks meet the requirements for organization of multi-level structure. In general, the requirements are as follows: at subscriber level – improving the quality of communication to maintain network connectivity; at the trunk level – providing network coverage, scalability, fault-tolerance, taking into account redundancy of paths, *QoS*; at the core level of the network – the integration of data flows and access to higher-level networks.

For multilevel architecture of Future Networks, it is advisable to break down the structure synthesis into two stages [25]:

- at the trunk, the structure should ensure the connectivity of users with the necessary quantitative and qualitative indicators of the efficiency of the network (reliability, bandwidth, service quality, availability, scalability, etc.). An integral indicator of the quality of network operation is the efficiency of routing information flows between subscriber nodes and gateways, which allows us to estimate the function of cost control over information flows at the trunk level,
- at the subscriber (user) level, the structure of the network should allow solving the problem of selecting a node cluster controller and locating the gateway to interact with the backbone network level.

It is known that in order to improve the performance of complex networks, the number of levels of a hierarchical structure is reduced. Their number should take into account the opposite requirements, on the one hand, reducing data transmission delays, on the other – simplifying the design and operation of the network. The number of levels of modern networks is approaching ten. To maximize delays while maintaining its zonal architecture, the network should consist of three levels: core network, access networks, and user-level.

Accordingly, the access network integrates information that is sent between user nodes. The connection between the access network and the core of networks can be either single (for low cost networks) or multiple (for networks with high reliability). The access network is formed on the basis of the use of such topologies as a tree or a star.

The core of the network combines traffic that is sent between subscribers connected to the access network. Typically, the following topologies are used for its implementation: fully connected, star, ring, etc.

Under such an approach, the multilevel architecture of Future Networks can also be provided by three levels: the core of the network are network gateways that provide access to the wired infrastructure (Internet or other local networks); the access network is made up of access points, which arrange switching between mobile nodes and network gateways and allow to rapidly expand the coverage area at the trunk level of the network; the user level consists of mobile subscriber nodes that are connected to the wired infrastructure by direct contact with the network gateways (according to their location and transmission capabilities), or through access points as transit nodes. The modification of the infrastructure consists in adding / removing or refusing access points.

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The problems of constructing optimal structures of complex networks in the literature are given considerable attention. Thus, methods of the theory of hierarchical systems that are widely used to describe network structures, in particular flow management networks, allow the Future Networks to be presented as a multi-level system with a hierarchical structure.

It is known that the classical hierarchical structure is understood as the connection between elements of the system, in which (Fig. 3a): 1) each element of the system belongs (at least formally) to one of the levels of the hierarchy and can be connected only with elements of other levels; 2) for each element of the system on the network there is a single path that connects it with one of the elements of the higher level.

The hierarchy is described with the help of an oriented acyclic graph $H = \langle V, E \rangle$ set by a set of vertices V and a set of edges $E \subseteq V \times V$ (arcs between nodes). The vertices of the acyclic graph, which do not include the arcs, are called initial, from which arcs do not reach the terminal – the remainder – intermediate or internal. We will assume that the arcs in the hierarchy are directed "from the bottom up", so the initial vertices will be called vertices of the lower level (subsidiaries) and they are subordinate to the remaining vertices, which we will call vertices of the upper levels. This means that in the graph, a route can be built from the original to the terminal nodes and vice versa.

We denote $D_G(m)$ as the set of vertices V, for which the vertex m is the parent in the graph G and $P_G(m)$ – the set of parent vertices in the graph. For the considered problem, the hierarchy is superimposed over some finite set of initial vertices $W = \{w_1, ..., w_n\}, n > 1$ – this set is fixed, unlike the set of upper levels and it may differ for different hierarchies.

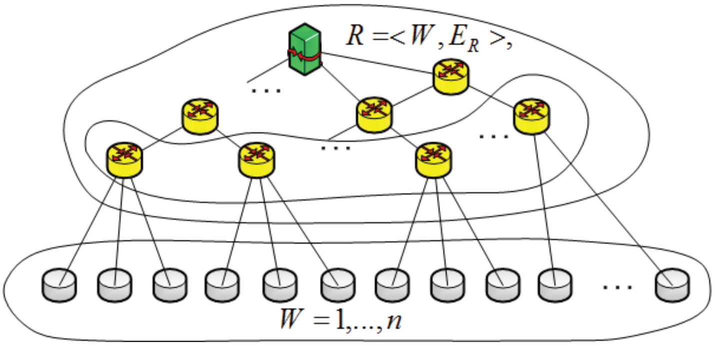
To emphasize that the set of the vertices $M = V \setminus W$ of the upper levels depends on the hierarchy H, we denote the set of vertices of the upper levels through M_H.

A characteristic feature of most of the management hierarchies that arise in the tasks of information processing is the presence among the terminal vertices of at least one "root" vertex, which directly or indirectly subordinates all the initial vertices of the hierarchy. For Future Networks, such a node is a gateway that performs the functions of managing all mobile user nodes in the system of routers – intermediate nodes of the upper levels of the hierarchy.

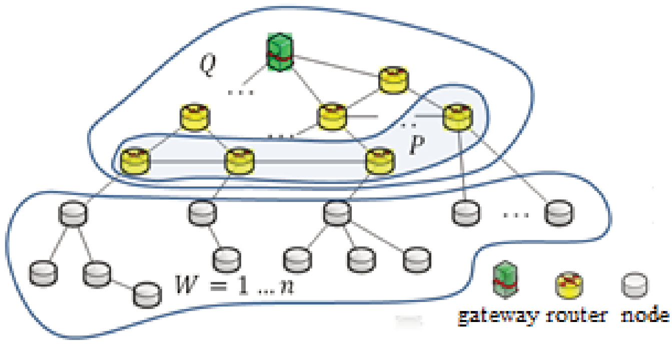
Features of network operation (excessive wireless communications, vertical and horizontal types of traffic) allow to modify the hierarchical structure of it by completing horizontal links between available elements (routers) of the same level (Fig. 3b). To do this, the routers are equipped with means of integration and differentiation of traffic.

The initial data for hierarchy synthesis is a finite set of vertices W, a set of hierarchies $\Omega \subseteq \Omega(W)$ and a cost function $C : \Omega \to [0, +\infty)$. The rule of finding the optimal hierarchy is described by expression (1).

If the number of elements in the lower level is not sufficient, this task can be solved by a complete overview of all possible hierarchies. However, as a rule, the number of possible hierarchies is significant, which does not even allow describing the function of costs. Then the cost function is determined analytically using the expression or algorithm, which depends on the structural parameters of the hierarchy - the number of intermediate (internal) vertices, their degree of connectivity, and so on.



a)



b)

Fig. 3 Structure of hierarchical network: a) homogeneous; b) heterogeneous with the use of inter-level links

Let's introduce a simplification with respect to the function of the cost of the hierarchy – this is the assumption of the additively of the cost function of the hierarchy. The costs $C(H)$ of any hierarchy H can be represented as the sum of the costs of the vertices of the upper levels:

$$C(H) = \sum_{m \in M} c(m, H) \tag{2}$$

where M – is the set of vertices of the upper levels of the hierarchy H and $c(m,H)$ – is the positive function called the cost function of the vertex, which defines its costs in the hierarchy H for each vertex m of set M.

From the standpoint of the task of forming a hierarchy, the initial vertices and the entire network of connections are located in a horizontal plane, and the hierarchy is built up vertically on this plane.

If the task of constructing the network structure of subscriber nodes can be solved by known methods used for MANET, mesh and ad-hoc networks, WSN, then the solution of the problem of efficient scaling of the entire network is possible only at the expense of the virtual organization of the hierarchical structure of its trunk level.

Fig. 4 shows an example of a three-tier network architecture: the bottom level in the horizontal plane shows the physical connection of user nodes using routers (access networks). The upper level forms the core of the network, which for the given example consists of one gateway. Intermediate level is a virtual representation of a hierarchical fractal structure, for which each element is subject to the principle of self-similarity of the same structure on the physical level.

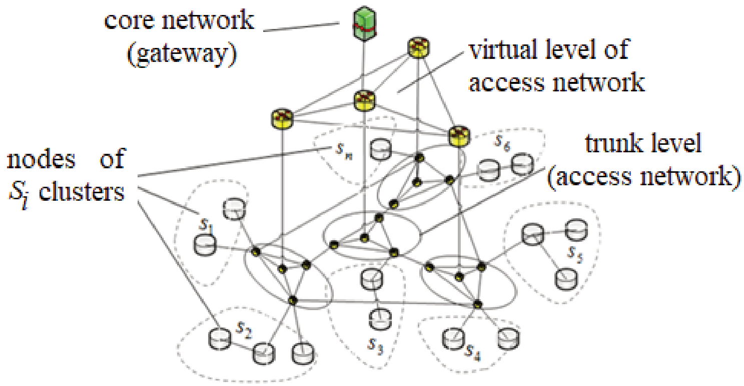


Fig. 4 Hierarchical structure of future networks with virtual fractal topology of access level to backbone network

Depending on the scale of the network, the number of intermediate (internal) levels of the hierarchical structure may be different, but the approach to estimating the total flow in the network remains the same.

For the same values of the input parameters of network, the hierarchical organization of the structure of the network with fractal topology of the trunk level has better time values, namely: the value of the average delay time with the increase in the intensity of the total flow is less than in the tree-like topology. This is due to the fact that in the hierarchical fractal structure, in contrast to the hierarchical tree-like, there are horizontal links between the elements (nodes) of one level. In classical hierarchical structures, the connections are only between elements of different levels.

The cost of the node m for managing the total flow in the network in terms of the theory of hierarchical systems is described by the expression:

$$c(m) = c\left(f_1^{\alpha} + \ldots + f_k^{\alpha}\right)^{\beta} \tag{3}$$

where f_k^{α} – the flow formed by k nodes of the lower level of the hierarchy; $\alpha = 0,\ldots,1$ – the share of the flow directed to the nodes of the higher level; $\beta = 1,\ldots,6$ – the constant that describes the rate of growth of costs with increasing levels of the hierarchy.

For a synthesized fractal network, in which the primary full mesh graph contains k = 4nodes, depending on the network load, the bandwidth of the communication channels, connecting the nodes of different levels and the proportion of the flow directed to the nodes of the higher level, the function of the charges is shown in Fig. 5.

Analysis of the results shows that when $\alpha = 1$, the network circulates vertical traffic, if $\alpha = 0$, it circulates in the horizontal traffic. If the total flow is equal to the bandwidth of the router, the flow control costs at the vertex m for the fractal and tree-like structure are the same.

If low-intensity traffic $f_m(k) < C_m$ is circulating in the network, fractal structure costs are larger than tree-like, which is due to the hardware complexity of the network's implementation, and vice versa, with increasing traffic $f_m(k) > C_m$, the advantages of a fractal structure with an increase in the share of traffic remaining at one level of the network $1-\alpha$ are significant.

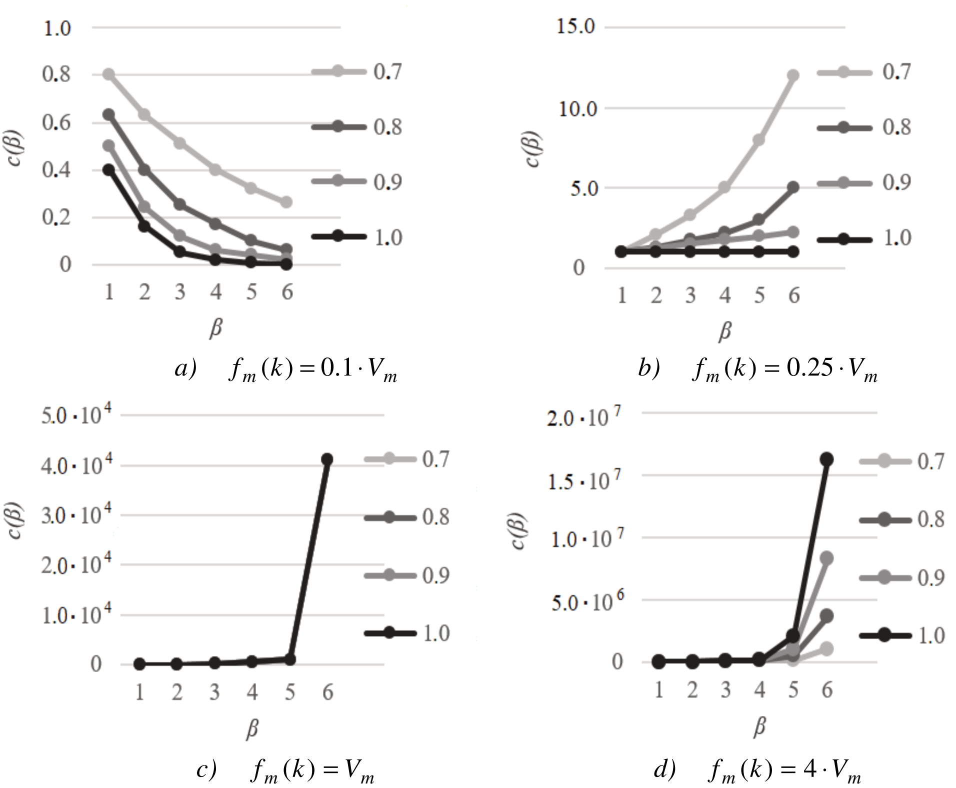


Fig. 5 Total flow control in the network depending on the traffic ratio $f_m(k)$ and bandwidth V_m: a) $f_m(k) = 0.1 \cdot V_m$; b) $f_m(k) = 0.25 \cdot V_m$; c) $f_m(k) = V_m$; d) $f_m(k) > V_m$

3. Conclusion

The topology of real networks differs from the classical fractal topology, and for the Future Networks it will likely be multifractal and heterogeneous. Characteristics of the primary graphs of multifractals will be the subject of further research.

The fractal topology implements network scaling, which ensures the rapid deployment of network segments in case of an increase in the number of users or an increase in the intensity of traffic. Horizontal connections in the fractal structure provide horizontal network traffic.

The implementation of the RDP routers will allow simultaneous support for the existing IP networks with horizontal traffic and switch networks to fractal architecture of the SDN with hybrid traffic.

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