Analysis of the Functioning of a Multi-Domain Transport Software-Defined Network with Controlled Optical Layer

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***Abstract*—In this paper we consider the technology of transport software-defined networks with controlled optical layer. We analyze the technical solutions of the transport software-defined network at all layers. The use of Super Channel technology is offered, which makes it possible to vary the bandwidth of the channel in a wide range for the clients. Comparison of the traditional network architecture with the architecture of transport software-defined networks is carried out. The advantage of the new architecture is a significant reduction in the time for providing the service on-demand for clients. Different variants of building the architecture of transport software-defined networks are considered. The technical features of existing and prospective transponders from the most well-known manufacturers, such as Nokia (fAlcatel-Lucent), Cisco, Huawei, etc., are studied with the aim of obtaining generalized characteristics. As a result of the work, the diagram of the complex model is proposed, which allows estimating the impact of all parameters of the multi-domain transport software-defined network on the possibility of providing the Bandwidth on Demand service. The proposed model is a multi-domain system with two layers of control (using domain controllers and a network-wide controller), supporting Bandwidth on Demand service between the two data centers through the establishment of a Super Channel between them. The developed modeling system can be used as a ready product.**

I. INTRODUCTION

Nowadays SDN (Software-defined networks) technology is becoming increasingly popular. In order to implement SDN technology fully, it is necessary to provide a network transport infrastructure that will allow all network resources, both optical network and IP / MPLS networks to be dynamically used to organize end-to-end data streams without changing the hardware. At the same time, the rapid development of data centers and cloud services (Infrastructure as a Service - IaaS, Platform as a Service - PaaS, Software as a Service - SaaS) led to the fact that in order to implement a cloud service, it is necessary to provide a route between two data centers with a guaranteed throughput. It is important that the created connection can be necessary only for the time of solving common tasks. This connection is called Data Center Interconnect. The organization of the route must be carried out in real time and with the necessary guaranteed throughput, and you may need to change the optical layer parameters.

Thus, the use of transport software-defined networks (T-SDN) implementing the Bandwidth on Demand service (providing bandwidth on the user's request) is considered optimal for solving such problems. To obtain an integrated model that allows to evaluate the impact of all parameters of the multi-domain T-SDN network on the possibility of providing a service, it is necessary to investigate the network transport infrastructure, possible versions of T-SDN architecture, and compare the technical characteristics of existing and prospective transponders in order to obtain generalized characteristics of transponders, which will be used as a set of initial data for modeling.

II. NETWORK INFRASTRUCTURE OF TRANSPORT SOFTWARE-DEFINED NETWORKS

For the technical implementation of SDN at the transport level (T-SDN), it is necessary to consider the technical solutions and capabilities of modern transport networks at all layers. There are four layers of transport networks: the layer of the optical cable structure; the layer of DWDM (Dense Wavelength Division Multiplexing); the layer of OTN (Optical Transport Network); the layer of IP / MPLS - the technology of Multi Protocol Label Switching.

At the first layer, the number of cables and optical fibers in each cable is defined. It is also important to note that not all fibers in the cable are used for data transmission, some fiber is reserved. Optical fibers G.652, G.653 and G.655 are the most commonly used. At present, they have almost reached the throughput limits. This is due to the limitations on broadband optical amplifiers (OA) operating in C and L bands. Also, restrictions are imposed on the level of optical power input, at which the fiber can begin to melt (approximately 1-2 W). It is believed that the power level of 17 dB is the limiting one, otherwise there is significant influence of the nonlinear effects in optical fiber.

These limitations do not allow the full implementation of T-SDN technology. However, it is possible to eliminate these problems. To increase the broadband of optical amplifiers, it is proposed to use EDFA (Erbium Doped Fiber Amplifier) or hybrid EDFA-Raman optical amplifiers operating in the C, L and S bands. This approach is considered, for example, for the implementation of a fiber-optic transmission system with a throughput of 25 Tbit/s [1]. Increasing the length of the regeneration section can be achieved by introducing Raman preamplifiers, raising the signal power by 14 dB at input. Currently, the bandwidth of optical fibers is less than 100 Tbit/s. However, not all the resources of optical fibers are totally used. It is possible to increase the capacity of optical fibers by applying various technical solutions at the DWDM layer.

To reach Petabit speeds, new types of optical fibers are created, for example, multi-core or few-mode fiber (with an increased core diameter), which will allow the use of space division or mode division multiplexing, respectively. Thus, even now the throughput of optical fibers can reach dozens of Tbit/s, and the prospective developments and solutions will make it possible to switch to Petabit speeds, which will create the basis for the introduction of T-SDN technology.

At the second layer (DWDM), according to ITU recommendations (G.694.1), the step between optical carriers, their number, and also the modulation formats are selected. Until recently, many standard fiber-optic transmission systems used a standard 50 GHz fixed grid and NRZ and RZ modulation formats, as well as their modifications. In this case, the channel data transfer rate per carrier reaches 10 Gbit/s (NRZ or RZ modulation format) or 40 Gbit/s maximum (NRZ ADPSK modulation format) [2]. Data in the SDH (Synchronous Digital Hierarchy) network can be transmitted, for example, using synchronous transport modules of the STM-16 and STM-64 levels on optical carriers with speeds of 10 Gbit/s and 40 Gbit/s, respectively. The number of optical carriers is invariable, which causes problems when transmitting packet traffic over SDH [3]. Also, multiplexers ROADM (Colored & Directional) are used, when a certain fixed frequency is tied to each port of the multiplexer and its ports are rigidly tied to a certain optical direction.

All this does not allow to change the bandwidth of the channel for the client flexibly. To implement T-SDN technology, it is necessary to be able to change dynamically the bandwidth provided to the client, i.e. there must be a reserve for changing the transmission rate of the client signal. This reserve is redistributed using special software installed on the controller [4]. At the transponder level, the optical channel capacity can be changed by applying different modulation formats.

Thus, the transition from binary modulation formats (NRZ, RZ and their modifications) with a maximum channel rate of 40 Gbit/s to multi-level modulation formats (QPSK, 8-QAM, 16-QAM and even 256-QAM) and the use of two polarizations allows to reach the transfer rate per optical carrier in 200 Gbit/s. At the moment, the optimal format is DP-QPSK (Dual Polarization Quadrature Phase Shift Keying) modulation with a channel transmission rate of 100 Gbit/s and a regeneration section length of about 5000 km.

It is important to note that the use of such complex modulation formats became possible only with the development of the technology of digital signal processors, which enabled the use of coherent methods of signal receiving and transmission.

Another technology that allows increasing the channel capacity for the user is Flexible Grid technology [5]. The frequency grid step, as recommended by the ITU (G.694.1), is selected in multiples of 12.5 GHz (37.5 GHz, 50 GHz, etc.). Flexible Grid technology assumes an arrangement of optical carriers with variable grid, which will allow dynamic use of bandwidth and use optical channels with different signal transmission rates [6].

To increase the spectral efficiency, a grid of 37.5 GHz should be selected. It's worth mentioning that there are already developments (for example, T8 or Nokia (fAlcatel-Lucent) companies), which allow to use this technology and reach 25 Tbit/s throughput. Flexible Grid technology allows increasing the bandwidth of the DWDM by more than a third, and also use 120 optical channels instead of 88.

The Flexible Grid technology is the basis for applying another technical solution to increase the channel capacity for the client. Super Channel technology is based on the replacement of several optical carriers with a low transmission rate with one channel with a high transmission rate (for example, 400 Gbit/s). The spectrum of the DWDM signal consisting of superchannels is presented in Fig. 1.

The optical carriers of one superchannel are called subcarriers. Optical superchannels are routed and switched to networks as a whole.

In a variety of ways, choosing a particular parameter of the optical signal can dynamically change the bandwidth of the superchannel. So, applying 2 subcarriers, a 50 GHz frequency grid and BPSK modulation format, the channel capacity can reach 50 Gbit/s, and the transmission distance is 10000 km. If we want to have a channel with a capacity of 400 Gbit/s, then we should use a DP-16QAM modulation format, also 2 subcarriers and a 50 GHz frequency grid. In this case, the length of the regeneration section will be reduced to 300-500 km [7].

This circumstance should be taken into account when designing new fiber-optic telecommunication systems or upgrading existing ones.

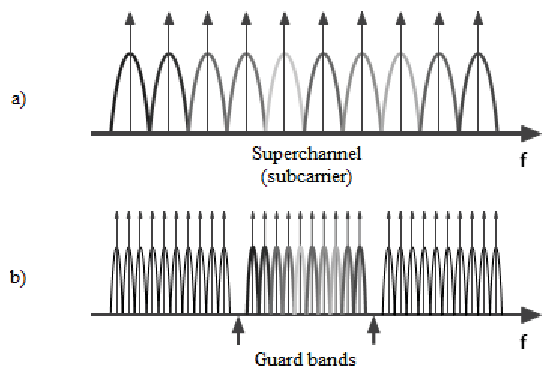

Fig. 1. Spectrum of a DWDM signal consisting of super channels: (a) spectrum of one superchannel, (b) spectrum of DWDM signal

The T-SDN technology is realized by providing to the client a path with the required bandwidth using superchannel technology. In addition, network flexibility can be achieved by moving from ROADM (Colored & Directional) to ROADM (Colorless & Directionless), where there is no fixed frequency binding to a particular multiplexer port and the wavelength from any port can be routed in any optical direction.

Thus, to increase the bandwidth of the client's channel, it is necessary to use: coherent methods of information receiving and transmission; polarization multiplexing; application of multi-level formats of modulation; a dense grid of frequencies, and also technology Flexible Grid; Super Channel technology; ROADM with colorless and directionless ports.

Using transponders that support the above technical solutions will allow the introduction of T-SDN technology at the DWDM layer. It is important to note that the choice of modulation formats, the frequency grid and the creation of super channels with the required bandwidth occurs at the program level using a controller, according to the SDN technology concept.

At the third layer (OTN), the type of transponder for a particular optical carrier is selected. In this case, data are placed in data units (for example, in ODU 1-an optical data unit of first order) and service streams over the wavelengths of the optical carriers. The data transfer rate in various OTN technology structures is presented in Table I. As it can be seen from Table I, OTN technology offers a wide range of transport structures for placing a client signal. Also, high-speed optical channels can be filled with low-speed service streams. For example, 8 streams with 1 Gigabit Ethernet layer speed can be placed in ODU 0 units, and then over the optical channel 10G (ODU 2). SDH traffic can also be packaged in OTN technology transport structures. It is important to note that in order to increase the length of the regeneration section, the verification fields with Forward Explicit Correction (FEC) codes can be used. As for the introduction of T-SDN technology, equipment already exists (for example, Nokia (fAlcatel-Lucent) that can support the functions of centralized OTN cross-connect with a performance of more than 9.6 Tbit/s [8].

At the fourth layer, IP / MPLS select the number and location of routers in the network. According to the definition [9], in the IP / MPLS network it is possible to organize flexible services of the second (VPLS) or third layer (VPRN), which enable the organization of client channels with a given bandwidth. However, the process of rearranging the bandwidth of the client channel takes considerable time and requires automation, which can be solved by using SDN technology.

TABLE I. THE DATA TRANSFER RATE IN VARIOUS OPTICAL TRANSPORT NETWORK TECHNOLOGY STRUCTURES

OTU-Optical Transport Unit	ODU-Optical Data Unit	Transmission rate
-	0	1.25 Gbit/s
1	1	2.5 Gbit/s
2	2	10 Gbit/s
3	3	40 Gbit/s
4	4	100 Gbit/s

At present, the convergent of optical technologies (DWDM) is taking place with packet technologies at all layers, including access layer. As for the metro layer, Metro Ethernet technology is connected to optical networks (DWDM / OTN). Service routers IP / MPLS are used on the convergent periphery. The core layer of the transport network is based on high-performance IP routers that use the capabilities of optical networks (DWDM / OTN). Such networks are called the Packet-Optical Transport System (P-OTS). Already on the basis of P-OTS it is possible to build T-SDN.

Thus, all layers of the transport network were analyzed, on the basis of which it can be concluded that the transition to T-SDN technology can be made only after the introduction of new technological solutions. It is important to consider the complex interaction of all layers in the transition to T-SDN technology. To switch to this technology, it is necessary to change the network infrastructure (Fig. 2), which was mentioned above.

According to the considered capabilities at the layer of IP / MPLS there is a routing and Ethernet switching of service streams (L2/L3). At the layer of SDH, SONET and OTN, multiservice cross-channel switching (L1) is implemented. The DWDM layer implements cross-connects the optical channels (L0). The layer of the optical cable structure remains unchanged at all stages.

At the first stage, the following layers were available: IP / MPLS layer; SDH, SONET and OTN layer; and DWDM layer. By integrating DWDM and SDH, SONET and OTN layers, we will get a convergent OTN / DWDM network. With further integration with the MPLS layer, we have a single convergent, scalable, multiple access network, which will allow dynamic creation of connections and provision of services with a minimum cost per bit. Such a transport network infrastructure will allow the implementation of T-SDN technology to be fully implemented.

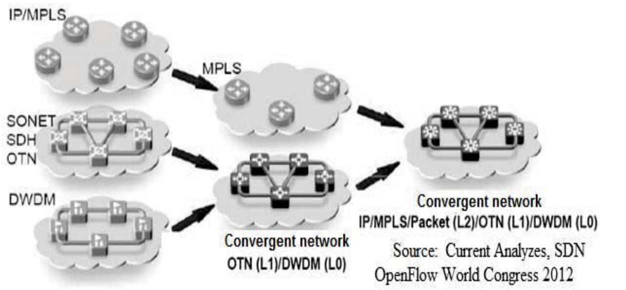

Fig. 2. Stages of changing the network transport infrastructure

III. TRANSPORT SOFTWARE-DEFINED NETWORK ARCHITECTURE

In the traditional transport network architecture, three layers of management are distinguished: operation support system (OSS), layer of network management system (NMS) and element management system (EMS), and transport network layer WDM / OTN / IP/MPLS (Fig. 3). SBI (Southbound Interface) provides interaction with network elements (NE), and NBI (Northbound Interface) interacts with OSS. At the same time, on the NBI it is necessary to implement the multi-technology and multi-vendor interface for operating system support (MTOSI), and on the SBI it is possible to use network management protocols such as Q/3, SNMP, TL1.

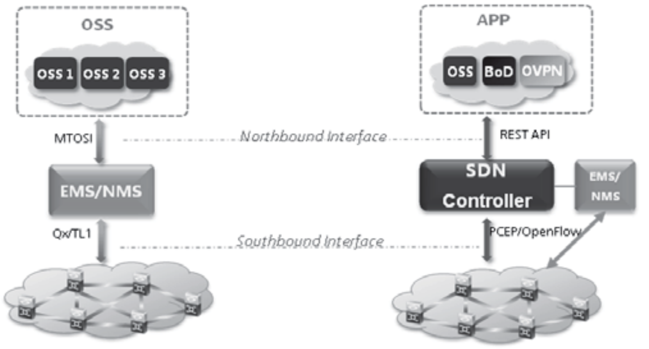

Fig. 3. Comparison of the traditional network architecture and SDN network architecture

The OSS function allows performing the following tasks: Resource / Inventory Management; Performance Management; Fault Management; Trouble Ticketing; SLA Management; Order Management; Fraud Management; Service Provisioning Management; Security Management; Accounting Management.

It is important to note that all these tasks are performed on a hierarchical basis (from OSS to NMS, then to EMS, which in turn manages NEs, such as routers, switches or photonic switches). In traditional control systems, the solution of such hierarchical tasks is a complex and time-consuming process, for example, when creating a new route for an IP stream with the need to reconfigure optical transponders, switches and routers, it may take from a few hours to several days.

In transport software-defined networks (Fig. 3), the interaction between applications (OSS, BoD-Bandwidth on Demand, OVPN-Optical VPN) and SDN controller occurs through the Representational State Transfer Application Programming Interface (REST API), which provides convenient management through simple operations . The SBI uses real-time protocols, such as PCEP (Path Computation Element Protocol) and OpenFlow, which provide information exchange between the controller and network devices in real time.

Such a T-SDN model conforms to the ONF and IETF standards. It distinguishes infrastructure layer, management or control layer, orchestration layer and layer of applications. It is important to note that T-SDNs are primarily focused on providing transport services, such as providing Bandwidth on Demand, creating different VPNs (OVPNs). In this work a particular interest is focused on introduction of a service to provide Bandwidth on Demand to the client.

In T-SDN, the task of managing transport NEs is performed in such a way that the process of providing the service to the client is automated, and the changes in the network infrastructure will be coordinated and will take place without deteriorating the quality of other transport services.

At present, research and developments in the field of T-SDN are being carried out actively. Scientific research of a number of companies, that have practical experience in implementing SDN, are of particular interest. So, the Chinese company Huawei offers its vision of T-SDN architecture (Fig. 4) [10].

At the infrastructure layer, the Metro network nodes and the Backbone network nodes are presented, which perform the functions of Photonic Switch, supporting WDM/OTN technologies. Data Center Interconnect is organized through Data Center controller. The main task of this layer is to transmit data from one port to another, i.e. ensuring the process of data transmission. The SBI of Domain Controller is used to manage NEs.

Transport SDN controller is the main element of the management plane and it supports the following functions: abstracts information about network elements in the infrastructure layer; receives information about the status of network resources in real time through SBI; provides transfer of control commands to network elements for creation and support of data transmission processes; provides the adaptation of the network to the resulting changes in the infrastructure to ensure a normal process of data transmission through the network; provides interaction with the upper levels of orchestration and applications through standard interfaces NBI (North Bound Interface).

The orchestration layer functions provide the Topology View, end-to-end network management, the definition of the Service Model and Policy Management. In this case, the interaction with the SDN controller is carried out through standard NBIs.

The application layer is presented by an open service platform that provides support for both applications developed by Huawei and applications supplied by other manufacturers.

The use of NMS network management systems and centralized operation of OSS provides the basic functions of managing network elements FCAPS: (F) Fault Management; (C) Configuration Management; (A) Accounting Management; (P) Performance Management; (S) Security Management.

With the evolutionary transition from traditional networks to T-SDN, these systems are irreplaceable network functions.

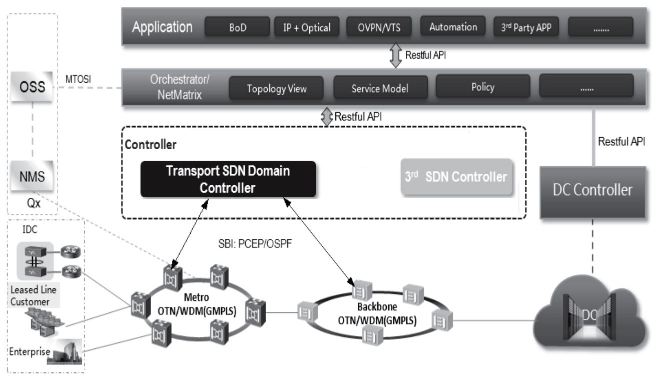

Fig. 4. Huawei T-SDN network architecture

The following protocols can be used on the SBI: PCEP and OSPF (Open Shortest Path First). The NBI is built according to the concept of REST, which is defined by the IETF, which provides flexibility, simplicity and scalability of the interaction between the SDN controller and applications.

Another example of the T-SDN architecture is the concept of Netcracker [11]. This example is interesting for research by considering the multi-domain structure for large and extended transport networks. There is a large transport network, which is divided into separate domains (Fig. 5), each of which has its own T-SDN Domain controller that manages all network elements of the domain.

At the upper-layer, a network-wide T-SDN controller is used to coordinate both domain controllers and data center controllers. It ensures the establishment of end-to-end services. The controller has a hierarchical structure, since there are very high performance requirements for managing such a network. As a lower layer controller, a T-SDN domain controller is used, and as an upper-layer controller a T-SDN network controller is used. (Fig. 6).

The domain controller manages only part of the network and controls the transport network devices. The upper-layer controller manages only domain controllers.

Such abstraction from communication with the network infrastructure allows to increase system performance. The network management tasks are decomposed and delegated to the lower layer controllers. The upper-layer controller receives data about the operation of the domain, processes them, and takes further actions.

In other words, the upper-layer controller views a whole group of devices as one device.

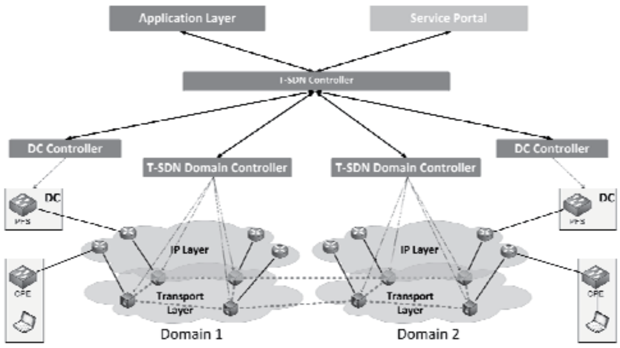

Fig. 5. Multi-domain transport network architecture

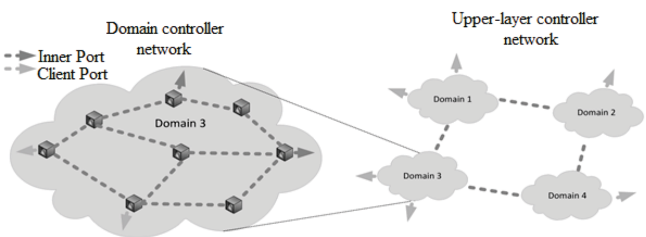

Fig. 6. Formal view of T-SDN at different layers

This concept, on the one hand, improves the performance, but on the other hand, it allows to browse the entire network with cross-domain connections, that can not be controlled at the domain layer, because they are not in the domain T-SDN controller's zone of visibility. This approach allows to create a client service across the entire network: from input into the provider's network, to the output from it. As a result, this approach helps to increase efficiently network management, to optimize routing, to provide high reliability and availability.

IV. Comparison of technical characteristics of existing and prospective transponders

Currently, there are many proposals for the implementation of T-SDN using different transponders. In order to obtain generalized characteristics of transponders for our model, we will perform a comparative analysis of existing and prospective transponders used in multiservice transport platforms from the most well-known telecommunication companies: Nokia (fAlcatel-Lucent), Cisco, Huawei, Juniper Networks and the Russian company T8. The technical characteristics are taken from official documents from sites of these companies. We will take into consideration the following characteristics: supported transmission rates; applicable modulation formats; used frequency grid, support for Flexible grid; the maximum number of channels; operating bands.

The results of comparison of transponders according to the listed criteria are presented in Table II (* - characteristics that can be achieved with the introduction of modern technical solutions).

It is important to note that not all possible transmission rates should be considered for this research (platforms support a wide range of speeds from Mbit/s to Tbit/s), but only those that can really be used to provide service between two data centers.

Transponders of all manufacturers support the most used transmission rates of 10, 40 and 100 Gbit/s. However, this is not enough for the organization of the Suprer Channel with the required transmission rate, since the necessary intermediate values can be much lower or higher than the indicated rates, which will lead to inefficient use of network resources, and, consequently, to significant material costs. The broadest set of transmission rates are available from Nokia (fAlcatel-Lucent) transponders. Cisco and T8 transponders also support transmission rates that allow flexible organization of Suprer Channel, for example, they realize the possibility to transmit a 400 Gbit/s channel using two 200 Gbit/s subcarriers. It is worth noting that the company Nokia (fAlcatel-Lucent) is now developing the organization of the channel in 400 Gbit/s on a single carrier.

The supported transmission rates are considerably determined by the used modulation formats. For low-speed channels (up to 10 Gbit/s) the NRZ modulation format is suitable. It is supported by all proposed transponders. To implement the 40 Gbit/s channel, there exist many modulation formats. The most widely used modulation formats are DPSK, RZ-DQPSK, NRZ ADPSK (supported by Nokia (fAlcatel-Lucent) transponders, Cisco and T8), and DP-QPSK with coherent receiving. Huawei company proposes using the DP-BPSK modulation format for 40 Gbit/s rate. For high-speed 100 Gbit/s and 200 Gbit/s channels, it is necessary to use the DP-QPSK and DP-16QAM modulation formats, respectively. Of the transponders in question, only Huawei equipment does not yet support the DP-16QAM modulation format. The use of high-order modulation formats leads to a significant reduction in the length of the regeneration section. Thus, the optimal modulation format for the rate of 100 Gbit /s is DP-QPSK (the regeneration section is more than 4000 km (maximum 8000 km) with a 50 GHz frequency grid and about 2600 km with a 30 GHz frequency grid). And for the rate of 200 Gbit/s the optimal format modulation is DP-16QAM (the regeneration section is 500-1022 km). For a 40 Gbit/s channel with the DPSK modulation format, the regeneration section is about 1600 km [12], and for the NRZ ADPSK modulation format the regeneration section is 2000 km. The creation of high-speed channels of 400 Gbit/s, 1 Tbit/s and more requires the use of Super Channel technology.

Used frequency grid determines the maximum number of subcarriers in the used spectral band. All transponders support standard grids of 50 GHz and 100 GHz, but such grids do not allow for a flexible change in bandwidth when creating a Super Channel. The Flexible grid technology allows flexible use of the spectral band. This technology is supported by transponders from Nokia (fAlcatel-Lucent), Huawei and T8. Company Nokia (fAlcatel-Lucent) now allows the use of a 50 GHz, 62.5GHz and 100 GHz frequency grids, that provides transmission system capacity of 19.2 Tbit/s, and the use of a grid with 37.5 GHz will significantly increase the capacity of the system in the future. The Huawei frequency grid can vary from 37.5 GHz to 400 GHz, thereby increasing the system capacity to 25.6 Tbit/s. The T8 company suggests using a non-standard frequency grid of 33 GHz. The laboratory experiments of the system with such frequency grid and 270 subcarriers are already actively carried out, which makes it possible to increase the capacity of the transmission system to 27 Tbit /s.

Most transponders from Table II support C-band and L-band. Only transponders from Huawei and Juniper Networks are currently operating in the widely used C-band. It is important to note that the laboratory experiments of Nokia (fAlcatel-Lucent) transponders operating in the S-band as well are also being actively conducted. This research will significantly increase throughput in the future.

The maximum number of channels is significantly determined by the functions supported by the transponder (applied frequency grid, modulation formats and operating bands). Transponders from Nokia (fAlcatel-Lucent), Cisco and T8 support up to 192 channels (96 in C-band and in L-band) with a 50 GHz grid and 100 Gbit/s channel rate. The transponders of Huawei and Juniper Networks operate only in C-band, but Huawei transponders have support for Flexible grid technology, which allows to reach the capacity of 25.6 Tbit/s now, while the transmission capacity of Juniper Networks reaches only 9.6 Tbit/s (96 channels). The use of Flexible grid technology allows transmission system of Nokia (fAlcatel-Lucent) to support up to 58 channels at 400 Gbit/s and frequency grid of 75 GHz. As a result, the capacity increases to 23.2 Tbit/s. The equipment of the company T8 will allow up to 270 channels at 100 Gbit/s in the future.

Thus, having analyzed the main technical characteristics of transponders from leading manufacturers, it can be concluded that not all transponders support Flexible grid and Super Channel technologies. The most functional is the transponder of Nokia (fAlcatel-Lucent), which supports a wide range of transmission rates and corresponding required modulation formats, Flexible grid technology, and a prospective S-band. All this allows flexible change of the bandwidth of the channel for the client, which will provide the service of the Super Channel. As for Huawei and T8 transponders, they have the necessary characteristics too, although Huawei transponders still work only in the C-band, but support the Flexible grid technology.

TABLE II. COMPARATIVE CHARACTERISTICS OF TRANSPONDERS OF DIFFERENT MANUFACTURERS

Companies and multiservice transport platforms	**Transmission rates, Gbit/s**	**Modulation formats**	**Frequency grid, GHz (*Flexgrid*)**	**Maximum number of channels**	**Bands**
Nokia (fAlcatel-Lucent), (1830 PSS capacity 19.2 Tbit/s, 23.2 Tbit/s *)	1.25, 2.5, 4, 10, 11, 40, 43, 100, 200, 250, 400 (2×200 or 1×400*), 500 (5×100 or 2×250)	NRZ, BPSK, DPSK, 8-QAM, QPSK, DP-QPSK, DP-NRZ BPSK, DP-16QAM,	*37.5**, 50, *62.5*, *75**, 100	192 (96 in C-band and 96 in L-band) at 100 Gbit/s, 58 at 400 Gbit/s*	C , L, S*
Cisco, (ONS 15454, capacity 19.2 Tbit/s)	1.25, 2.5, 10, 40, 100, 200, 400 (2×200), 1000 (Super Channel)	NRZ, RZ-DQPSK, DQPSK, DPSK, DP-QPSK, DP-16QAM	50, 100	192 (96 in C-band and 96 in L-band) at 100 Gbit/s	C, L
Huawei, (Optix OSN 9800, capacity 25.6 Tbit/s)	1.25, 2.5, 10, 40, 100 200, 400, 1000 and 2000 (Super Channel)	NRZ, RZ, DP-BPSK, DP-QPSK	50, 100 *37.5-400*	40 (100 GHz grid), 80 (50 GHz grid)	C
Juniper Networks, (BTI 7800, capacity, 9.6 Tbit/s)	10, 40, 100, 200, 400 (2×200)	NRZ, DP-QPSK, DP-16QAM	50, 100, 200	96 in C-band at 100 Gbit/s	C
T8, («Volga» capacity 19.2 Tbit/s , 27 Tbit/s*)	2.5, 10, 40, 100,150, 200, 400 (2×200), 1000*	NRZ, NRZ ADPSK, DPSK, DP-QPSK, DP-8QAM, DP-16QAM	*33**, 50, 100	192 (96 in C-band and 96 in L-band) at 100 Gbit/s , 270* at 100 Gbit/s (C+L)-band	C, L

To obtain a complex model that allows to evaluate the impact of all parameters of the multi-domain T-SDN network on the possibility of providing the Bandwidth on Demand service, the most important are the following results of the analysis. When modeling, it is necessary to take into account specific types of transponders from a certain manufacturer, since this is important for creating a Super Channel. Thus, the generalized features of transponders were obtained on the basis of data on technical capabilities and future developments of Nokia (fAlcatel-Lucent), Huawei and T8. Table III shows the modulation formats, transmission rates and frequency grids supported by the transponders used in our model. Transponders operate in the C-band and L-band, which will allow to apply our model to most modern transmission systems, however, if necessary, the model can take into account the prospective S-band.

The transponder reset time is 50ms. The maximum transmission distance without regeneration is limited by both the used modulation format and the selected grid spacing. For low-speed subcarriers up to 10 Gbit/s inclusive, the use of NRZ modulation formats makes it possible to transmit them to a distance of up to 10000 km without regeneration in a 50 GHz frequency grid. The use of a grid at 37.5 GHz reduces the regeneration section slightly, since the width of the laser emission spectrum is relatively small. For subcarriers with a transfer rate of 40 Gbit/s with the DPSK modulation format which are used with other type of subcarriers the transmission distance is 1600 km, and for the NRZ ADPSK modulation format the transmission distance is 2000 km. The choice of the modulation format depends on the set of modulation formats supported by the transponders and on the distance between the network elements. For subcarriers with a transmission rate of 100 Gbit/s using the DP-QPSK modulation format, the transmission distance for a 50 GHz frequency grid is more than 4000 km (80 channels), and for a 33 GHz frequency grid, the transmission distance is about 2600 km (up to 270 channels in perspective). For subcarriers with a transmission rate of 200 Gbit/s, only the DP-16QAM modulation format is used, and the maximum transmission distance can be 1022 km. For a superchannel with a transfer rate of 400 Gbit/s (2 × 200 Gbit/s, with 50 GHz frequency grid), the transmission distance is 300-500 km.

TABLE III. GENERALIZED CHARACTERISTICS OF TRANSPONDERS

Transmission rate, Gbit/s	Modulation Format	Frequency Grid, GHz
1.25	NRZ	50, when creating a Super Channel 37.5
2.5	NRZ	
10	NRZ	
40	DPSK, NRZ ADPSK, DP-QPSK	
100	DP-QPSK	
200	DP-16QAM	50

Thus, based on the results of the analysis, a set of initial data on the use of transponders with software control was obtained. It takes into account the implementation constraints (bandwidth, transmission distance for the used types of modulation formats and the number of subcarriers) as well as ranges of possible values, taking into account existing technical abilities and prospective solutions.

V. DESCRIPTION OF THE MODEL FOR THE MULTI-DOMAIN TRANSPORT SOFTWARE-DEFINED NETWORK

The diagram of the complex model that allows to evaluate the influence of all parameters of the multi-domain T-SDN on the possibility of providing the Bandwidth on Demand service is presented in Fig. 7. The model includes two data centers between which it is necessary to provide the Bandwidth on Demand service through the organization of Super Channel. The model is a multi-domain T-SDN system with two layers of control. At the upper-layer, a network-wide T-SDN controller is used to coordinate domain controllers. It provides the end-to-end service. As a lower-layer controller, a domain T-SDN controller is used, which manages only part of the network and manages functions of the transport network devices. The network management tasks are decomposed and delegated to the lower-layer controllers. The upper-layer controller receives data about the operation of the domain, processes them and takes further actions, it perceives the whole group of devices as one device. It is important to note that it views the entire network together with cross-domain connections.

The model can be used on a network with *m* domains, but for clarity, a network with two domains will be modeled. On-demand connections are established by the customer interacting with a bandwidth broker/scheduler application hosted on an SDN controller. The parameters of the requested connection are transmitted through the NBI API of the network controller. The northbound API allows customer clients and applications to request SDN communications services directly from the control layer. Connection parameters can include UNI source and destination, bandwidth, maximum delay, protection level (1 + 1, 1: 1, etc.).

In addition, the connection can be immediately created for a specific time or at a specially planned time in the future, or for an indefinite period. The scheduler application first checks the request for the required maximum total bandwidth, and then applies the path computation element (PCE) calculation module to determine whether the path can be provided. If the network controller determines that the domains can provide it, then a connection is created either immediately or at the scheduled time through the network-wide controller. Domain controllers also use the PCE to identify the best path in the domains and issue commands via the OpenFlow transport NE to establish a bi-directional connection.

Transport network elements *(1 ... n)* can exchange service information with the domain controller via the OpenFlow protocol. For each NE the types of transponders are defined for a specific optical carrier.

For the technical implementation of the research model, a research stand was developed. It consists of a number of virtual machines (VMs) that emulate the components of the multi-domain T-SDN. The software basis for the stand is OS Linux Ubuntu 14.07 LTS with the KVM hypervisor, which is used to manage and interconnect the VMs (Fig. 8).

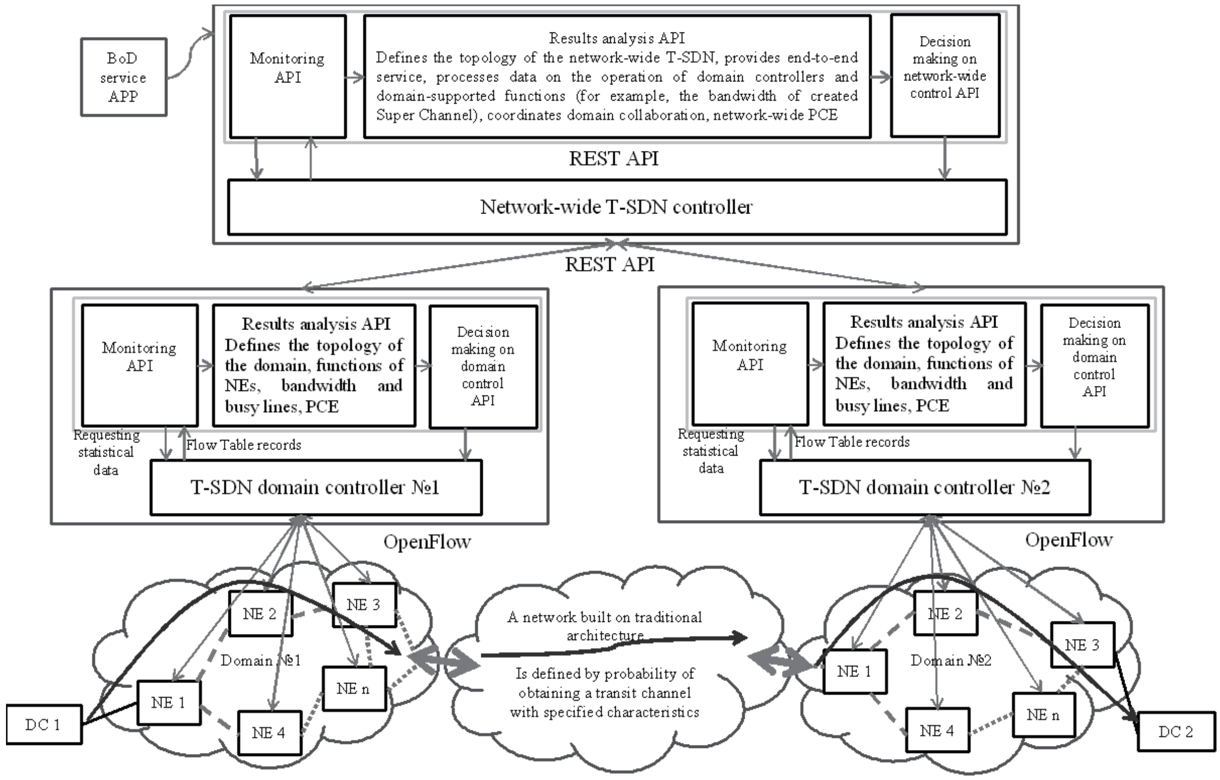

Fig. 7. The diagram of the model for the research

The VMs interconnection type is based on the results of performed analysis and on the diagram of the model for the research (Fig. 7). The research stand consists of six virtual machines: one VM for each domain controller, a VM of the network-wide controller, VMs for emulation of two domains and a network built according to the traditional architecture. To emulate two domains and a network built according to the traditional architecture the software environment Mininet is used. The platform ONOS - Open Network Operating System is selected as the SDN-controller. Traffic is generated by means of the D-ITG (Distributed Internet Traffic Generator) program. This research model allows getting all the necessary data to assess the possibility of providing the service Bandwidth on Demand.

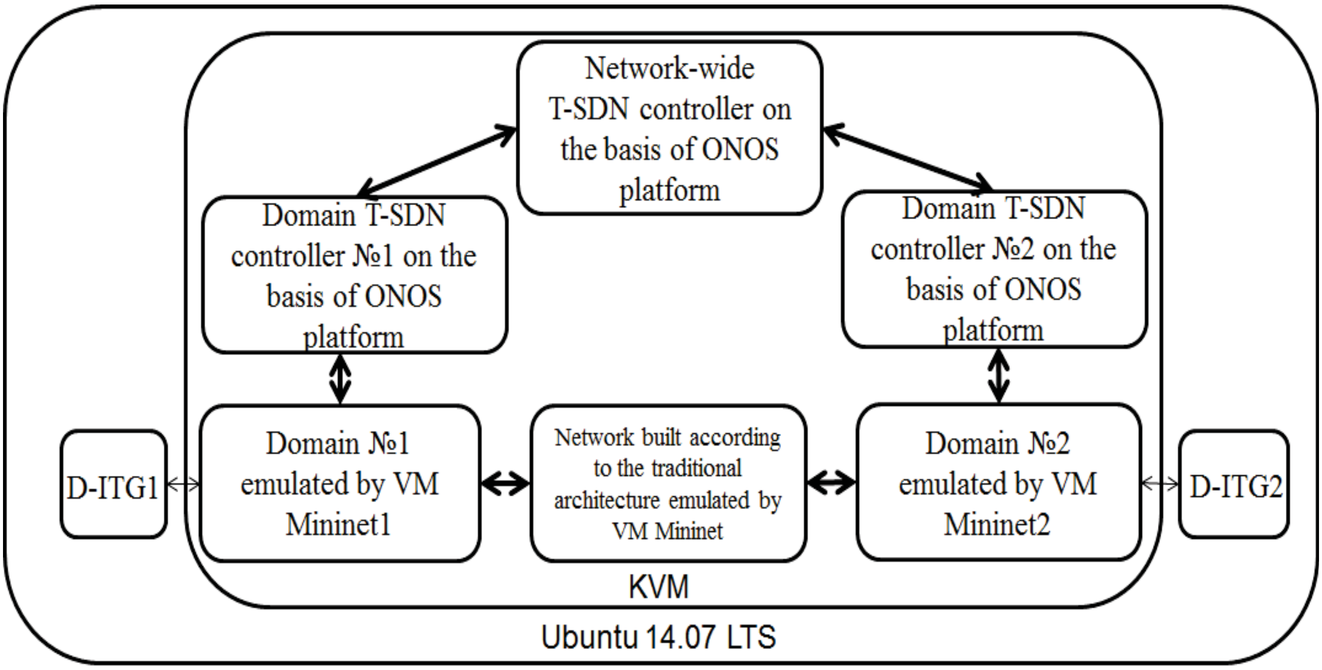

Fig. 8. The diagram of a developed research stand

VI. Conclusion

In this paper a profound analysis of the functioning of the multi-domain transport software-defined network T-SDN with a controlled optical layer was conducted with the aim of developing a complex model that allows to estimate the influence of all network parameters on the possibility of providing the Bandwidth on Demand service.

The network transport infrastructure T-SDN was considered, the technical possibilities for creating a channel with dynamically changing bandwidth for creating the Super Channel and providing the Bandwidth on Demand service were estimated. Possible T-SDN architectures were studied, on the basis of which a model for research has been developed. In order to select the transponders for the model, a comparative analysis of transponders from the most well-known manufacturers was carried out.

As a result of the analysis, a diagram of the model for the research was proposed, functions of the main elements of the diagram were described, the topology of the network was specified. A research stand was developed.

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