Mathematical Description of Control Problems in SDN Networks

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Abstract: To improve the efficiency of networks, fully automate the processes of network management, administration and technological, reduce the time to market for modern services, ensure the introduction of new technologies throughout the network, and not gradually introduce them at individual sites, operators are starting the practical use of software-defined networks with virtualization network functions. The optimality of the decisions made, largely depends on the capabilities of the control plane in the SDN architecture. To obtain optimal solutions, a mathematical formulation of control problems is required, using real indicators of the functioning of telecommunication networks as input data. The paper proposes mathematical models of the process of functioning of the SDN network in the main modes of operation: in the mode of planned changes in the structure of the network, in the mode of normal functioning, when all performance indicators are within the specified values, in the overload mode. The results obtained make it possible to determine the list of required network elements, to distribute functions between the elements of the control system, to develop requirements for the monitoring system to collect the necessary initial data and to determine the interaction algorithm of the elements to obtain optimal solutions in the process of network management.

1 INTRODUCTION

Traditional telecommunication networks represent a set of specialized physical devices such as routers, switches, soft switches, firewalls, and other equipment. These devices were created based on specific hardware and software platforms from different vendors. Therefore, the implementation of new modern services on networks, as a rule, requires replacing the old equipment set with a new one. This approach leads to the occurring of long design cycles, purchase of the necessary equipment and conducting commissioning tasks. All this negatively works on the efficiency of providing users with new products and services. Maintaining and control such a network control is ineffective and expensive costs. Therefore, quite often, investments in the development of the network to satisfy subscribers' requests could significantly exceed the growth in income from the services` provision.

However, nowadays the networks of telecommunications operators are mainly consisting of "monolithic physical" network elements, where control functions, administration and transmission of user data are performed by physical devices. Often the network is built using network elements from the same producers, as this makes it easier to ensure compatibility. Deployment of services, modification ("upgrades") of equipment or services are performed by tuning on each network element and requires close coordination of internal and external operator's resources. This approach makes the operator's network inflexible, makes it difficult to implement new services and functions, and also increases the operator's dependence on specific vendor solutions.

Therefore, now, the issues of building networks based on the SDN concept are increasingly on the agenda of research organizations, universities and mobile operators. Representatives of the Open Networking Foundation (ONF) consortium make hereby the main contribution to the development of this area. ONF is an non-profit organization dedicated to advancing of SDN and introduction of NVF [1].

For the moment, ONF has developed a number of documents describing the principles of construction and performance of SDN networks. In [3, 4, 5, 6] general requirements, system approaches and

and performance of SDN networks. In [3, 4, 5, 6] general requirements, system approaches and generalized architecture of SDN networks are reviewed. In works [2, 7, 8, 11] tasks and features of the protocols used in solving various problems in SDN networks are considered. Ins [9, 10, 12] the features of the construction of SDN network elements and the order of their interaction in the process of maintaining traffic flows are described. In [3, 4, 5, 6, 14] the principles of constructing an optical transport network and are given recommendations to provide the safety of their operation are considered. The most complete and systematized material is presented in [8, 9]. In articles [10, 11, 12, 13] various aspects of servicing information flows are investigated and focused on the need to meet the requirements for providing network security.

It should be noted that most of the research work focus on the ways of practical implementation of SDN principles during network deployment. Also considered are possible structure and order of interaction of the main elements of the network, such as a controller and a switch. At the same time, one of the most difficult and important issues in SDN networks is to provide the solution of managing problems under different operating conditions. The solution of these tasks can be assigned both to the controller or network operating system, and to control applications located in the control plane. In this research, possible formulations of control problems and their formalized representation as mathematical models (equations) shall be analyzed.

2 SDN MANAGEMENT TASKS

Native existing telecommunications networks based on "monolithic physical" elements are forcing an increasing number of telco operators to take part in the development of the ONF consortium. They develop experimental areas of the network in which studies of the practical availability of any given solution are carried out.

2.1 Analyses of SDN Requirements

Let's consider what requirements telecom operators impose on networks based on SDN technology:

Improve operational efficiency:

- provide flexibility and scalability of the entire operator's network;
- fully automate the processes of performing operations, administration (Management) and maintenance, OAM;
- solve the problems of dynamic control of traffic flows in real time, in accordance with the current state of network resources;
- operatively create the necessary types of services what require the combined usage of several services.

Transform business models:

- reduce the output time of modern services to market;
- provide that innovations are quickly extended across the entire network, rather than being set in across the network sections;
- quickly and efficiently create and provide demanded services (Agile);
- increase the quality of the process of providing services to end users.

All this is achieved through the implementation of new approaches to the building of SDN networks, specifically:

- separating the control plane from the data plane;
- providing programmability of the level of control of network resources, computing resources, resources data storage and service orchestration;
- providing the ability to virtualize most types of equipment and system network functions;
- implementation of providing users with the same set of services, regardless of whether a set of physical devices is used for this or their representation in the form of virtual machines;
- unification of protocols and automation of solving problems of network elements` configuration;
- providing an individual mechanism for administration and allocation of resources in the network upon request of various services and functions;
- automation of management processes in the deployment of network elements and business processes.

Assurance the conditions for meeting these requirements will allow creating telecommunication networks with high efficiency and competitive ability at the telecommunications market.

2.2 Components of SDN Architecture

Let's analyze the components of the SDN network architecture, which are defined in ONF TR-502 [3]. At the same time, focus will be on the elements that are directly involved in the management process. As far as, at the present stage, SDN networks will operate in the environment of traditional networks, we will consider an architecture that takes this factor into account (Figure 1). We will also take into account the possibility of interference in the control process of a human operator.

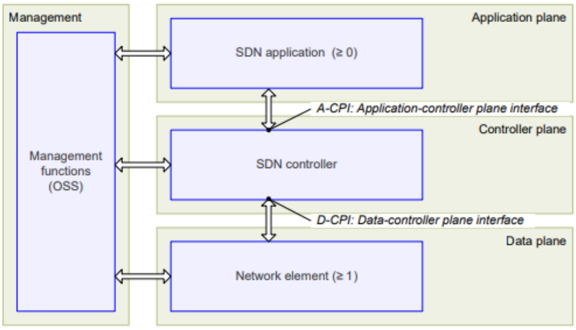

Figure 1: SDN with function management.

At Figure 1 are showed the following main components of SDN:

- data plane;
- controller plane;
- application plane;
- management plane.

The data plane consists of one or more network elements. Each element contains a set of resources for forwarding or processing traffic. Resources are abstractions of the basic physical capabilities of an element. The data plane interacts with the control plane through southbound interfaces, often called as SBI.

The application plane can contain one or more applications. Each application has exclusive control over the set of resources provided by one or more SDN controllers. Applications can:

- interact with each other directly;
- act as SDN controller;
- place their network requirements on the controller plane through northbound interfaces, often called NBI.

The control plane consists of a set of SDN controllers. Each SDN controller manages a set of resources for one or more network elements in the data plane. The minimum functionality of an SDN controller should provide:

- processing application requests that are assigned to it;
- isolate applications' work from each other. For this the SDN controller can communicate with other SDN peer-to-peer controllers;
- respond to network accidents to restore normal operation after a failure;
- manage the competing requirements of different applications.

An independent element of the architecture is the management functional block. This block provides for the possibility of intervention in the control process of a human operator. It can be used:

- for initial configuration of network elements;
- when assigning areas controlled by different SDN controllers;
- to configure the SDN area controller.

At the controller level, the human operator can set up:

- policies that define the scope of control that are provided to SDN applications;
- limits of allocated resource;
- list of system parameters to be monitored.

At the application level, the human operator usually configures:

- contracts and service level agreements (SLA);
- algorithms for solving control problems;
- device priority level when solving problems together.

At all levels of control, human-operator sets up a security policy that allows distributed functions to communicate safely with each other.

2.3 Components of SDN Architecture

To solve management issues, it is necessary to have elements that collect information, analyze it, make decisions and communicate commands to executive agents. These elements in the SDN architecture are agents and coordinators.

At Figure 2 are showed the agents and coordinators in the SDN controller and network elements.

Agents support the concept of sharing (co-use) or virtualizing default (essential) resources. For example, agents own next information:

- which network elements ports are monitored by SDN;
- which elements of the virtual network are open for SDN applications;
- how to isolate the service of one client from another one.

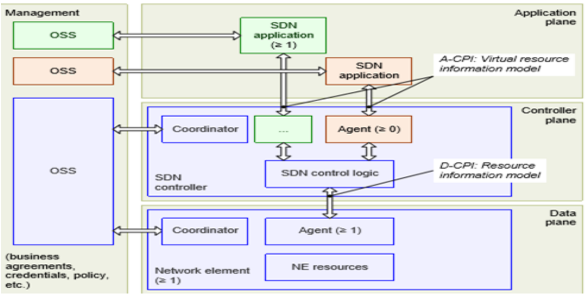

Figure 2: Agents and Coordinators in SDN Architecture.

In the SDN controller, different agents can control the network at different levels of abstraction and provide the execution of different set of functions. The purpose of the SDN control logic is to:

- provide arbitration between the network requirements of all SDN applications;
- develop a set of instructions for a network element (NE) and implement them through NE agents.

Coordinators in the NE and SDN controller establish specific resources and policies to customer from the human operator. Multiple agents can exist on any network element and SDN controller. But there is only one logical control interface. Therefore, at any time, only one coordinator works per one network element or an SDN controller.

3 FORMALIZED STATEMENT OF CONTROL ISSUES FORMED ON THE CONTROLLER PLANE

The functioning of SDN networks requires constant management of its elements. In this case, the nature of the tasks to be solved can be considered in different conditions as:

- planned deployment or deployment of SDN network;
- normal operation mode of the SDN network;
- functioning of SDN networks in extreme situations (case).

For each of the above-mentioned conditions can be earmarked specific groups of control tasks. So, for the first case, the group of management tasks with a planning-changing structure should include:

- analysis of the plan of deployment, rolling up or reorganization of the network;
- analysis of an existing, or required (when deploying), or becoming free (rolling up) network resource;
- analysis of requirements for quality of service QoS and network bandwidth;
- formation of a load distribution plan (LDP);
- making decisions on the distribution of the network resource, providing the implementation of the LDP with minimal time, material-technical and other types of costs;
- formation of teams for network elements that implement the decisions.

The tasks of this group can be solved in the controller plane or assigned to applications. It should be noted that one of the main tasks of network planning is to determine the required performance of the branches and the channel resource that provide service of the incoming load with a desired quality.

This task can be formulated like this. Determine the required performance of each branch of the network, expressed in the number of standard channels $\{V_{ij}\}$, in the network given by the graph G(N,M), and formulate the LDP, which represents a matrix M_v = $\{\mu^{v}_{ij}\}$ set of paths μ^{v}_{ij} (v = $\overline{1,k}$) transferring information between each pair of Switching center (SC) i,j (i,j = $\overline{1,N}$, where N is a number of SC in the network), with order v (v= $\overline{1,k}$) their occupations, providing service to the incoming load the network Z by I information directions J_{ij} (i,j = $\overline{1,N}$) with a given quality of service P_{ij} with the minimum total involved channel capacity V_Σ of the branches m_{ij} (i,j = $\overline{1,N}$), i.e.

$$\{V_{ij}\} = f(M_v = \{\mu^{v}_{ij}\}),\ (i,j = \overline{1,N},\ v = \overline{1,k}) \quad (1)$$

under the using restrictions:

$$\begin{cases} V_\Sigma = \min \sum_{i=1}^{N} \sum_{j=1}^{N} V_{m_{ij}} \\ P \geq \max\{P_{ij}\}, (i,j = \overline{1,N}) \\ P_{ij} = \prod_{i=1}^{N} \left[1 - \prod_{j=1}^{N} \left(1 - p_{m_{ij}}\right) \right] \\ Z = \sum_{i=1}^{N} \sum_{j=1}^{N} z_{ij}, (i,j = \overline{1,N}) \\ k = \max \frac{1}{M} \sum_{i=1}^{N} \sum_{j=1}^{N} k_{ij}, (i,j = \overline{1,N}) \\ N, M, V_{ij}, k_{ij} \in G(N,M) \\ I = N(N-1) \ \ at \ J_{ij} \neq J_{ji} \end{cases}$$

where P - permissible denial-of-service rate in the direction of communication;

P_{ij} – real probability of fault of service in information directions ($i,j = \overline{1,N}$);

k_{ij} - utilization factor in branches m_{ij} ($i,j = \overline{1,N}$);

z_{ij} – incoming load to the service in information directions;

$p_{m_{ij}}$ - probability of losses on branches;

M - number of branches in the network.

Equation (1) is rather complicated and solutions cannot always be obtained. Therefore, sometimes solve a little simplified problem:

$$V=\{V_{ij}\},(i,j=\overline{1,N}) \quad (2)$$

using the following system of restrictions:

$$\begin{cases} V_\Sigma = \min\sum_{i=1}^{N}\sum_{j=1}^{N} V_{m_{ij}} \\ M_\nu = \{\mu_{ij}^{\nu}\},(i,j=\overline{1,N},\nu=\overline{1,k}) \\ P \ge \max\{P_{ij}\},(i,j=\overline{1,N}) \\ P_{ij} = \prod_{i=1}^{N}\left[1-\prod_{j=1}^{N}(1-p_{m_{ij}})\right] \\ Z = \sum_{i=1}^{N}\sum_{j=1}^{N} z_{ij},(i,j=\overline{1,N}) \\ k = \max\frac{1}{M}\sum_{i=1}^{N}\sum_{j=1}^{N} k_{ij},(i,j=\overline{1,N}) \\ N,M,V_{ij},k_{ij} \in G(N,M) \\ I = N(N-1) \ at \ J_{ij} \ne J_{ji} \end{cases}$$

That is, in the process of calculating the required channel capacity of the network branches, it is assumed that the LDP is given.

During the normal functioning of the network, the main management tasks are:

- monitoring the technical condition of network elements and estimation the values of the parameters of its functioning;
- method, recording and processing of data on the technical failures in network elements, leading to a degradation in the parameters of the functioning of communication directions;
- control of indicators of bandwidth of branches and directions of communication;
- establishing the facts of deviation of parameter values from the established norm;
- identification of places and causes of network failure;
- determining a way to restore the normal network functioning;
- making a decision to restore the normal network functioning;
- formation of a team for control objects in order to implement the decision.

The main task of the SDN network controller is to form a LDP (load distribution plan) that provides the specified characteristics and efficiency of the network equipment use, i.e.:

$$M_\nu = \{\mu^{\nu}_{ij}\} \ (i,j=\overline{1,N},\ \nu=\overline{1,k}) \quad (3)$$

under the following system of restrictions

$$\begin{cases} V^* = \max\left\{\sum_{i=1}^{N}\sum_{j=1}^{N}\left[f(P_{ij})(V_{ij}-V_{ij}^0)\right]\right\} \\ V = \{V_{m_{ij}}\},(i,j=\overline{1,N}) \\ Z = \{Z_{m_{ij}}\},(i,j=\overline{1,N}) \\ P \ge \{P_{ij}\},(i,j=\overline{1,N}) \\ P_{ij} = \prod_{i=1}^{N}\left[1-\prod_{j=1}^{N}(1-p_{m_{ij}})\right] \\ V_{ij},Z_{ij},P_{ij},p_{m_{ij}},N,M \in G(N,M) \end{cases}$$

where V^* - the number of channels, deleting which from the branch does not lead to $P_{ij} > P$;

$$f(P_{ij}) = \begin{cases} 1, if \ \max\{P_{ij}\} \le P \\ \gamma_{ij}, if \ \max\{P_{ij}\} > P \end{cases};$$

$$\gamma_{ij} = \begin{cases} 1, or \ V_{ij} \ge V_{ij}^0 \\ 0, or \ V_{ij} < V_{ij}^0 \end{cases};$$

V_{ij} - number of channels in a branch;

V^0_{ij} - required number of channels in a branch m_{ij} to service the incoming load with a given quality.

The value of V^* can acts as an assessment of management efficiency when comparing different SDN management applications.

If the LDP generated by the SDN controller is close to optimal, then in the normal functioning of the communication network, as a rule, the operational-technical requirements will be satisfied.

An extreme situation may turn out to be one of the conditions for the “normal” functioning of a controlled communications network. Under such conditions, the role of SUSS is especially significant, and the tasks solved by this system have a number of specific features. These tasks, first of all, can be attributed:

- organization of a system for collecting data about damage on the elements and sections of a controlled communication network;

- method and processing of data about the damage on the elements and sections of the network;
- determining the type of damage to elements and sections of the network;
- accounting of the resource of the managed network, providing the functioning of the existing communication directions;
- accounting for the reserve network resource and determining the places of its exploitation;
- estimation of the expediency of introducing restrictions on incoming load;
- formation (re-formation) of LDP for the existing directions of communication;
- clarification of requirements for the quality of service in the areas of communication;
- making decisions for the restoration of damaged network elements, reducing the influence of damaging factors;
- formation and transmission of commands to control objects and providing control over their implementation.

In the event of extreme situations on the communication network associated with the impact of external damaging factors on it, the Controller is transferred to a special operating mode. To estimate the situation on the Controller communication network, using (3) will be solved. As a result, it may turn out that the quality of service $P < \max\{P_{ij}\}$ in some directions of communication below the required standards. Under these conditions, first of all, an attempt is made to bring the characteristics of the network to the required standards by redistributing and limiting the number of ways of transmitting information in terms of communication directions, i.e.

$$\nu = \min \sum_{i=1}^{N} \sum_{j=1}^{N} \left[\nu_{ij} - \nu'_{ij} \right] \left(i, j = \overline{1, N} \right) \tag{4}$$

under the following restrictions:

$$\begin{cases} M_{\nu} = \left\{ \mu_{ij}^{\nu} \right\}, \left(i, j = \overline{1, N}, \nu = \overline{1, k} \right) \\ V = \left\{ V_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ Z = \left\{ Z_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ P \geq \max\left\{ P_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ N, M, Z, P, V, M_{\nu} \in G\left(N, M \right) \end{cases},$$

where ν_{ij} - possible ways of transferring information in the direction,

ν'_{ij} ways of transmitting information, which are prohibited from usage.

If the measures taken do not lead to the desired result, then the next step is to put into operation the existing reserve of forces and means. At this stage, the minimum required additional resource is determined, which provides that the network characteristics are brought to the required standards, i.e.

$$V_0 = \min \left\{ \sum_{i=1}^{N} \sum_{j=1}^{N} \left[m_{ij} \left(V_{ij} - V_{ij}^{0} \right) \right] \right\} \left(i, j = \overline{1, N} \right) \tag{5}$$

with the following restrictions:

$$\begin{cases} M_{\nu} = \left\{ \mu_{ij}^{\nu} \right\}, \left(i, j = \overline{1, N}, \nu = \overline{1, k} \right) \\ Z = \left\{ Z_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ P \geq \max\left\{ P_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ N, M, Z, P, V, M_{\nu} \in G\left(N, M \right) \end{cases},$$

$$m_{ij} = \begin{cases} 0, if\; V_{ij} \geq V_{ij}^{0} \\ 1, if\; V_{ij} < V_{ij}^{0} \end{cases},$$

where V^0_{ij} – the actual (available) resource of channels in the network;

V^0_{ij} - the resource of channels in the network, which is necessary to ensure a given quality of service;

V_0 - the number of channels that must be added to the network in order to bring the characteristics to the required standards.

If the required number of channels exceeds the available reserve, then the next measure to bring the network characteristics to the required standards may be to limit the incoming load, i.e.

$$Z_0 = \min \sum_{i=1}^{N} \sum_{j=1}^{N} \left(Z_{ij} - \Delta Z_{ij} \right) \left(i, j = \overline{1, N} \right) \tag{6}$$

under the following restrictions:

$$\begin{cases} M_{\nu} = \left\{ \mu_{ij}^{\nu} \right\}, \left(i, j = \overline{1, N}, \nu = \overline{1, k} \right) \\ V = \left\{ V_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ P \geq \max\left\{ P_{ij} \right\}, \left(i, j = \overline{1, N} \right) \\ N, M, P, V, M_{\nu} \in G\left(N, M \right) \end{cases},$$

It should be noted that it is rather difficult to obtain a solution to control problems (4), (5), (6) for real large-scale switched networks.

Sometimes, in the event of extreme situations, instead of the requirement to bring the network characteristics to the normalized values, a condition is set to provide the possible bandwidth with the maximum acceptable quality. In this case, the specified quality of service is provided for customers and messages of higher categories. At the same time, the quality of service for the lower categories is not standardized.

The availability of a large number of random factors affecting the conditions for the functioning of SDN networks leads to the advisability of introducing integrated management of the structure, flows, parameters and modes of network operation in order to maintain their basic characteristics within the required norms.

4 CONCLUSIONS

In this work, an analysis of the functioning process of the control (managment) level of the SDN network was conducted. Hereby, the purpose and functions of the list of the main elements were conducted. Also, the process of interaction of system elements in solving arising problems was analyzed.

The main attention is paid to the determination of the list of tasks for SDN network management in various modes of exploitation. A possible variant of a group of practical control problems, which might arise in real networks was conducted.

An important work aspect of this consideration is the formalization of management tasks. For this, three most widespread modes of network functioning, were considered, along with possible methods for solving control problems. For the latter ones, their mathematical description was given. The advantage of mathematical models for solving control problems is that the values of real indicators of network functioning are used as input data and parameters.

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