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## Article

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Technology audit and production reserves

*Reference:* Korenko, Dmytro/Cherevatenko, Oleksii et. al. (2022). Creation of the method of multipath routing using known paths in software-defined networks. In: Technology audit and production reserves 4 (2/66), S. 19 - 24.  
<http://journals.urau.ua/tarp/article/download/262787/259233/605533>.  
doi:10.15587/2706-5448.2022.262787.

This Version is available at:  
<http://hdl.handle.net/11159/12780>

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# CREATION OF THE METHOD OF MULTIPATH ROUTING USING KNOWN PATHS IN SOFTWARE-DEFINED NETWORKS

The object of the research is the creation of a multipath routing algorithm for software-defined networks (SDN) including known paths, subject of the research is network parameters, designed according to a certain topology and using the developed algorithm. One of the most problematic aspects of contemporary computer networks (including applied SDN networks) is overloading. This results in harder control and limiting traffic and amount of users. Most routing algorithms that are used today have a rather large time complexity.

In the course of the study, the following methods were used: study of known routing solutions for SDN networks and results of their application, method of path metric computation on the given topology by the amount of «hops» (transitions between network nodes), optimization of procedure for finding the path using SDN technology capabilities. These methods were united and integrated into the development of the overall routing algorithm, which is proposed in this article.

The proposed multipath routing algorithm allows for the improvement of the process of traffic construction in the SDN network. This was achieved by decreasing the time complexity of the routing algorithm through the usage of previously known paths in the topology without the need to construct new ones. Involvement in the modification of the algorithm of forming distance vectors facilitated timely network reconfiguration in case its state changed. Using a centralized SDN controller made it possible to increase the stability of the network and save all configuration data in one place. The above factors make it possible to deploy an SDN network on an Edge architecture.

Obtained results of the application of the multipath routing algorithm allow to consider it effective when compared with previously proposed algorithms, based on obtained results from a practical network model, where the proposed multipath routing algorithm is used. This is because the research task was formed correctly, and the solution for this task gave correct results. Results of using the described algorithm are demonstrated, and an analysis of the obtained results is conducted, which makes it possible to confirm the accuracy of scientific research.

**Keywords:** software-defined networking, multipath routing, known routes, distance vector.

Received date: 27.06.2022

Accepted date: 09.08.2022

Published date: 15.08.2022

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## How to cite

Korenko, D., Cherevatenko, O., Rusinov, V., Kulakov, Y. (2022). Creation of the method of multipath routing using known paths in software-defined networks. *Technology Audit and Production Reserves*, 4 (2 (66)), 19–24. doi: <http://doi.org/10.15587/2706-5448.2022.262787>

## 1. Introduction

Until today, computer networks have grown big with a massive amount of data and users in them. Because of this, the process of management of the network becomes harder so as building private virtual networks (VPNs), network data centers, distributed clusters, and using cloud technologies. Edge architecture has been suggested as a solution to distribute the workload between devices, however, edge usually consists of smaller, less powerful devices, therefore a way to distribute tasks on the network efficiently, without resorting to specialized hardware [1]. Software-defined networking (SDN) is now being widely used to solve these problems. It allows to increase the efficiency of network equipment, reduce operating costs, and increase network manageability and security. Using

SDN it is possible to manage the network on the software level and by that, it is possible to increase the control of transmitting data in the network [2].

Taking the growing popularity of the SDN technology into account, there is a problem of developing methods for constructing traffic especially for SDN architecture principles. In the general case, traffic engineering consists in distributing flows along selected paths. In this case, the choice of a path or the formation of a plurality of paths is determined by the given parameters of the quality of service (QoS) of the transmitted information and load balancing in the network [3].

One of the most promising ways to construct traffic in large-scale computer networks is the use of multipath routing. In this article let's describe the method of using this principle by reusing known paths to save resources while

transferring data in the network with focus on QoS, load balancing and avoiding of overloads. The last is provided by multi-path routing itself, as it can use different routes to decrease the load of the network [4].

Because most of the known algorithms have significant time complexity, the best practice is to use a wave algorithm for generating the maximum set of non-intersecting paths between two graph vertices, which differs from the known algorithms by minimal time complexity [5, 6].

Software-defined network has network management which is carried out at the software level using virtual switches and a central SDN controller. Centralized management of network devices allows to expand the functionality of the traffic construction procedure. Under centralized management, the SDN controller updates the routing information for the SDN switches by updating their routing tables to choose the best route based on the specified path metric.

Compared to distributed traffic engineering methods, the centralized method eliminates the need to exchange overhead information between network switches [7].

The use of a centralized multipath routing algorithm can improve network performance by 10–15 % by reducing the volume of service packets. This reduces energy consumption by approximately 41 % and increases the maximum utilization of communication channels by 60 % compared to distributed methods of traffic engineering and its balancing [8].

The use of the wave routing algorithm allows to simultaneously form the optimal set of paths not only between the initial and final nodes, but also from all intermediate nodes to the final node. This allows for effective balancing of traffic in computer networks [9, 10].

So, the problem is actual because of the increasing size of different networks and the number of their users. As traditional routing methods get more complicated, a new way of implementing routing information between multiple nodes is needed. SDN support is also needed as this technology spreads rapidly and has promising practical application.

Thus, *the object of research* is the creation of a multipath routing algorithm for software-defined networks (SDN) including known paths, subject of the research is network parameters, designed according to a certain topology and using the developed algorithm.

*The purpose of this research* is to develop a method of multi routing in the network, which would provide better network parameters such as throughput and number of users, than previous methods that were already created, and reduce the time complexity of the algorithm.

## 2. Research methodology

The centralized way of constructing traffic allows to optimize the process of forming routes by using previously formed paths.

When constructing traffic, a set of minimal non-intersecting routes is used. This reduces the likelihood of re-forming paths when the network topology or data link parameters change.

For example, for the topology shown in Fig. 1, there are two sets of minimal disjoint paths between vertices  $v_1$  and  $v_{12}$ .

$$P_1 = \{L_1(1,13), L_2(1,13), L_3(1,13)\},$$

$$P_2 = \{L_1(1,13), L_2(1,13), L_4(1,13)\}. \quad (1)$$

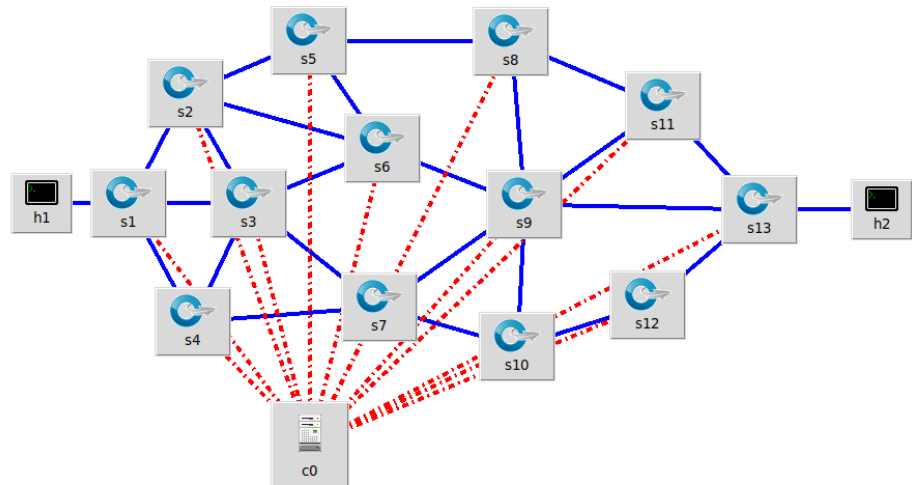
$$L_1(1,13) = (v_1 \rightarrow v_4 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12} \rightarrow v_{13}),$$

$$L_2(1,13) = (v_1 \rightarrow v_3 \rightarrow v_7 \rightarrow v_9 \rightarrow v_{13}),$$

$$L_3(1,13) = (v_1 \rightarrow v_2 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13}),$$

$$L_4(1,13) = (v_1 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8 \rightarrow v_{11} \rightarrow v_{13}). \quad (2)$$

As a path metric, let's use the number of transitions (hops) between network nodes. This metric is most often used in mobile computer networks.



**Fig 1.** The network's topology

When using a multipath routing algorithm by the distance vector for the path from vertex  $v_1$  to vertex  $v_{13}$ , a table of vectors of paths from the initial vertex  $v_s$  to the final vertex  $v_d$  towards the adjacent vertex  $v_a$  is formed (Table 1). The metric  $M_i$  is equal to the number of edges of the path  $l_i$ .

The presence of a path  $L_i(s,d)$  between the vertices  $v_s$  and  $v_d$  determines the tables of distance vectors from all intermediate nodes  $v_j$  of this path to the final node  $v_d$ . For a path  $L_1(1,13) = (v_1 \rightarrow v_4 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12} \rightarrow v_{13})$  the following path vector tables are formed (Tables 2–5).

Vertex  $v_1$  distance vectors

**Table 1**

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_1(1,13)$ | $v_1$ | $v_{13}$ | $v_4$ | 5     |
| $H_2(1,13)$ | $v_1$ | $v_{13}$ | $v_3$ | 4     |
| $H_3(1,13)$ | $v_1$ | $v_{13}$ | $v_2$ | 4     |
| $H_4(1,13)$ | $v_1$ | $v_{13}$ | $v_2$ | 5     |

Vertex  $v_4$  distance vectors

**Table 2**

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_1(4,13)$ | $v_4$ | $v_{13}$ | $v_7$ | 4     |

Vertex  $v_7$  distance vectors (first route)

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$    | $M_i$ |
|-------------|-------|----------|----------|-------|
| $H_1(7,13)$ | $v_7$ | $v_{13}$ | $v_{10}$ | 3     |

Table 3

Vertex  $v_{10}$  distance vectors

| $H_i(s,d)$   | $v_s$    | $v_d$    | $v_a$    | $M_i$ |
|--------------|----------|----------|----------|-------|
| $H_1(10,13)$ | $v_{10}$ | $v_{13}$ | $v_{12}$ | 2     |

Table 4

Vertex  $v_{12}$  distance vectors

| $H_i(s,d)$   | $v_s$    | $v_d$    | $v_a$    | $M_i$ |
|--------------|----------|----------|----------|-------|
| $H_1(12,13)$ | $v_{12}$ | $v_{13}$ | $v_{13}$ | 1     |

Table 5

For the path  $L_2(1,13) = (v_1 \rightarrow v_3 \rightarrow v_7 \rightarrow v_9 \rightarrow v_{13})$  the following path vector tables are formed (Tables 6–8).

Vertex  $v_3$  distance vectors

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_2(3,13)$ | $v_3$ | $v_{13}$ | $v_7$ | 3     |

Table 6

Vertex  $v_7$  distance vectors (second route)

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_2(7,13)$ | $v_7$ | $v_{13}$ | $v_9$ | 2     |

Table 7

Vertex  $v_9$  distance vectors (first route)

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$    | $M_i$ |
|-------------|-------|----------|----------|-------|
| $H_2(9,13)$ | $v_9$ | $v_{13}$ | $v_{13}$ | 1     |

Table 8

For the path  $I_3 = (v_1 \rightarrow v_2 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$  the following path vector tables are formed (Tables 9–11).

Vertex  $v_2$  distance vectors (first route)

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_3(2,13)$ | $v_2$ | $v_{13}$ | $v_6$ | 3     |

Table 9

Vertex  $v_6$  distance vectors

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_3(6,13)$ | $v_6$ | $v_{13}$ | $v_9$ | 2     |

Table 10

Vertex  $v_9$  distance vectors (second route)

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$    | $M_i$ |
|-------------|-------|----------|----------|-------|
| $H_3(9,13)$ | $v_9$ | $v_{13}$ | $v_{13}$ | 1     |

Table 11

For a path  $I_4 = (v_1 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8 \rightarrow v_{11} \rightarrow v_{13})$  the following path vector tables are formed (Tables 12–15).

SDN technology allows to optimize the procedure for forming new routes using already formed paths or their sections. For this purpose, in this paper it is proposed to form a matrix of vectors of optimal paths  $A = \|a_{i,j}\|$ , where  $a_{i,j}$  is the nearest node  $v_a$  to node  $v_i$  in the direc-

tion of node  $v_j$  with the minimum path metric. In the Table 16 adjacent vertices of all vertices of the optimal path  $L_3(1,13) = (v_1 \rightarrow v_2 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$  are showed. The result of path determination using the developed algorithm for the specified topology can be seen in Fig. 2.

Vertex  $v_2$  distance vectors (second route)

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_4(2,13)$ | $v_2$ | $v_{13}$ | $v_5$ | 4     |

Table 12

Vertex  $v_5$  distance vectors

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $H_4(5,13)$ | $v_5$ | $v_{13}$ | $v_8$ | 3     |

Table 13

Vertex  $v_8$  distance vectors

| $H_i(s,d)$  | $v_s$ | $v_d$    | $v_a$    | $M_i$ |
|-------------|-------|----------|----------|-------|
| $H_4(8,13)$ | $v_8$ | $v_{13}$ | $v_{11}$ | 2     |

Table 14

Vertex  $v_{11}$  distance vectors

| $H_i(s,d)$   | $v_s$    | $v_d$    | $v_a$    | $M_i$ |
|--------------|----------|----------|----------|-------|
| $H_4(11,13)$ | $v_{11}$ | $v_{13}$ | $v_{13}$ | 1     |

Table 15

Matrix of vectors of optimal paths

| $i \backslash j$ | $v_1$    | $v_2$    | $v_3$    | $v_4$    | $v_5$    | $v_6$    | $v_7$    | $v_8$    | $v_9$    | $v_{10}$ | $v_{11}$ | $v_{12}$ | $v_{13}$ |
|------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| $v_1$            | –        | $v_2$    | $\times$ | $\times$ | $\times$ | $v_2$    | $\times$ | $\times$ | $v_2$    | $\times$ | $\times$ | $\times$ | $v_2$    |
| $v_2$            | $\times$ | –        | $\times$ | $\times$ | $\times$ | $v_6$    | $\times$ | $\times$ | $v_6$    | $\times$ | $\times$ | $\times$ | $v_6$    |
| $v_3$            | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_4$            | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_5$            | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_6$            | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_7$            | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $v_9$    | $\times$ | $\times$ | $\times$ | $\times$ | $v_9$    |
| $v_8$            | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_9$            | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ | $v_{13}$ |
| $v_{10}$         | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ | $\times$ |
| $v_{11}$         | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ | $\times$ |
| $v_{12}$         | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        | $\times$ |
| $v_{13}$         | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | –        |

Table 16

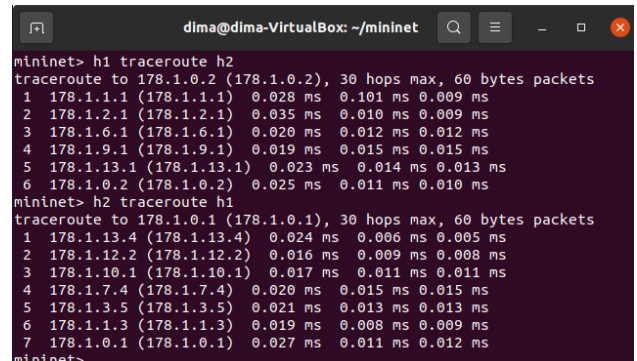


Fig. 2. Derivation of the optimal route for packet transmission from  $v_1$  to  $v_{13}$

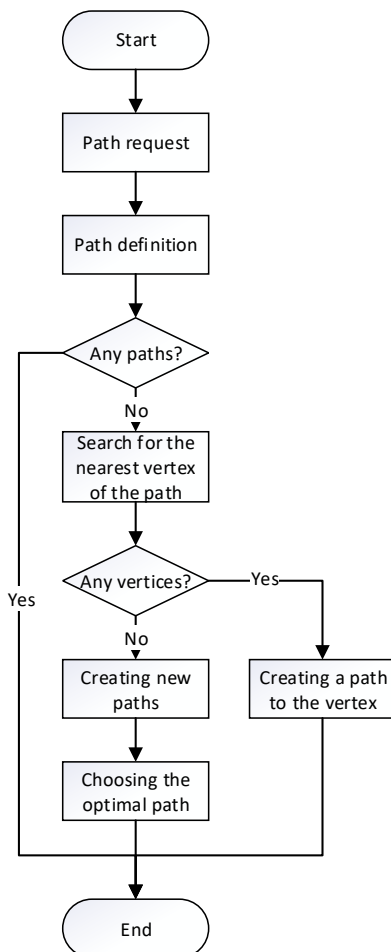
The values of the optimal path vectors are formed on the basis of the vertex distance vectors (Tables 1–15). Based on Table 16, the search and formation of optimal routes is carried out.

**3. Research results and discussion**

A block diagram of traffic construction is demonstrated in the Fig. 3.

It is also possible to use this method to distribute the workload over the network using edge architecture. One such example includes neural enabling AI on the premise. Such network might include multiple devices, having been assigned different roles, for example, sensors, that record and sift the data, and a more powerful computer to train the neural network. Let's analyze the creation of distance vectors  $R_1(v_1, v_{13}, v_a)$ ;  $R_2(v_3, v_{13}, v_a)$  and  $R_3(v_3, v_9, v_a)$  for a graph from Fig. 1.

Let's suppose there is the sensor from which it is necessary to send the data onto node that is performing machine learning tasks. For the path  $L_1(1,13)=(v_1 \rightarrow v_2 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$   $v_a$  corresponds to the value  $d_{1,13} \in D = \|d_{ij}\|$  and equals  $v_a = v_2$ . The path vector is formed  $R_1(v_1, v_{13})$  and its metric is in Table 17.



**Fig. 3.** The algorithm of creating the paths

**Table 17**

| Vertex $v_1$ chosen distance vector |       |          |       |       |
|-------------------------------------|-------|----------|-------|-------|
| $R_i(s,d)$                          | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
| $R_1(1,13)$                         | $v_1$ | $v_{13}$ | $v_2$ | 4     |

Let's see how the vector  $R_i(v_3, v_{13}, v_a)$  paths  $L_i(v_3, v_{13})$  can be created from the vertex  $v_3$  to  $v_{13}$ .

For the path  $L_i(v_3, v_{13})$  in the table  $D = \|d_{ij}\|$  there is no value for  $d_{3,13}$ .

*Stage 1.* When  $i=1$  a set of vertices  $V_1 = \{v_3\}$ . Based on  $E = \|e_{ij}\|$  let's define the set of vertices  $V_2 = \{v_1, v_2, v_4, v_6, v_7\}$  which are adjacent with a vertex  $v_3 \in v_1$ . Create paths from  $v_3 \in v_i$  to the set of vertices  $V_2 = \{v_1, v_2, v_4, v_6, v_7\}$ .

The path  $L_1(v_3, v_1) = (v_3 \rightarrow v_1)$ . Distance vector from  $v_3$  to  $v_1$  equals  $R_1(v_3, v_1, v_1)$ . The path's metric  $L_1(v_3, v_1)$  equals  $M_1(v_3, v_1) = 1$ .

The path  $L_2(v_3, v_6) = (v_3 \rightarrow v_6)$ . Distance vector from  $v_3$  to  $v_6$  equals  $R_2(v_3, v_6, v_6)$ . The path's metric  $L_2(v_3, v_6)$  equals  $M_2(v_3, v_6) = 1$ .

From the table  $D = \|d_{ij}\|$  for the vertex  $v_6$  let's define the vector  $R_1(v_6, v_{13}, v_9)$  of the path  $L_1(v_6, v_{13}) = (v_6 \rightarrow v_9 \rightarrow v_{13})$ . The path's vector  $L_1(v_6, v_{13})$  equals  $M_1(v_6, v_{13}) = 2$ .

A path is created  $L_2(v_3, v_{13}) = L_2(v_3, v_6) + L_1(v_6, v_{13})$  with vector  $R_2(v_3, v_{13}, v_6)$ .

The path  $L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$  with metric  $M_2(v_3, v_{13}) = 3$ .

Time complexity of path formation  $L_2(v_3, v_{13})$  decreases for 2/3 in comparison with that for the whole path.

The path  $L_3(v_3, v_2) = (v_3 \rightarrow v_2)$ . Distance vector from  $v_3$  to  $v_2$  equals  $R_3(v_3, v_2, v_2)$ . The path's metric  $L_3(v_3, v_2)$  equals  $M_3(v_3, v_2) = 1$ .

The path  $L_4(v_3, v_4) = (v_3 \rightarrow v_4)$ . Distance vector from  $v_3$  to  $v_4$  equals  $R_4(v_3, v_4, v_4)$ . The path's metric  $L_4(v_3, v_4)$  equals  $M_4(v_3, v_4) = 1$ .

The path  $L_5(v_3, v_7) = (v_3 \rightarrow v_7)$ . Distance vector from  $v_3$  to  $v_7$  equals  $R_5(v_3, v_7, v_7)$ . The path's metric  $L_5(v_3, v_7)$  equals  $M_5(v_3, v_7) = 1$ .

Thus, after the first iteration, these paths are formed:

$$L_1(v_3, v_1) = (v_3 \rightarrow v_1), M_1(v_3, v_1) = 1;$$

$$L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13}), M_2(v_3, v_{13}) = 3;$$

$$L_3(v_3, v_2) = (v_3 \rightarrow v_2), M_3(v_3, v_2) = 1.$$

$$L_4(v_3, v_4) = (v_3 \rightarrow v_4), M_4(v_3, v_4) = 1.$$

$$L_5(v_3, v_7) = (v_3 \rightarrow v_7), M_5(v_3, v_7) = 1.$$

Vectors' definitions  $R_1(v_3, v_1, v_1)$ ,  $R_2(v_3, v_{13}, v_6)$ ,  $R_2(v_3, v_{13}, v_2)$ ,  $R_2(v_3, v_4, v_4)$  and  $R_3(v_3, v_7, v_7)$  written in the table  $E = \|e_{ij}\|$ .

*Stage 2.* From the table  $E = \|e_{ij}\|$  let's define the vertex  $v_5$  which is adjacent with the end vertex  $v_2$  of the path  $L_2(v_3, v_2) = (v_3 \rightarrow v_2)$ . A path is being created  $L_2(v_3, v_5) = (v_3 \rightarrow v_2 \rightarrow v_5)$  with metric  $M_2(v_3, v_5) = 2$ . Distance vector from  $v_3$  to  $v_5$  equals  $R_2(v_3, v_5, v_2)$ .

From the table  $E = \|e_{ij}\|$  let's define the vertex  $v_{10}$  which is adjacent with the end vertex  $v_7$  of the path  $L_5(v_3, v_7) = (v_3 \rightarrow v_7)$ . A path is being created  $L_5(v_3, v_{10}) = (v_3 \rightarrow v_7 \rightarrow v_{10})$  with metric  $M_5(v_3, v_{10}) = 2$ . Distance vector from  $v_3$  to  $v_{10}$  equals  $R_5(v_3, v_{10}, v_7)$ .

From the table  $E = \|e_{ij}\|$  let's define the vertex  $v_2$  which is adjacent to the vertex  $v_1$  of the path  $L_1(v_3, v_1) = (v_3 \rightarrow v_1)$ . The vertex  $v_2$  is included in the path  $L_3(v_3, v_{13}) = (v_3 \rightarrow v_2 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$ . That is why the path from  $v_1$  to  $v_2$  does not extend.

From the table  $E = \|e_{ij}\|$  let's define the vertex  $v_7$  which is adjacent to the vertex  $v_4$  of the path  $L_4(v_3, v_4) = (v_3 \rightarrow v_4)$ . The vertex  $v_7$  is included in  $L_5(v_3, v_7) = (v_3 \rightarrow v_7)$ . Because of that the path from  $v_4$  to  $v_7$  does not extend.

Thus, after the second iteration, these paths are formed:

$$L_2(v_3, v_5) = (v_3 \rightarrow v_2 \rightarrow v_5), M_2(v_3, v_5) = 2;$$

$$L_5(v_3, v_{10}) = (v_3 \rightarrow v_7 \rightarrow v_{10}), M_5(v_3, v_{10}) = 2.$$

Vectors' definitions  $R_2(v_3, v_5, v_2)$ ,  $R_5(v_3, v_{10}, v_7)$  written in the table  $E = \|e_{i,j}\|$ .

Stage 3. From the table  $E = \|e_{i,j}\|$  let's define vertices  $v_6$  and  $v_8$  which are adjacent to the vertex  $v_5$  of the path  $L_2(v_3, v_5) = (v_3 \rightarrow v_2 \rightarrow v_5)$ . The path is formed  $L_2(v_3, v_6) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_6)$  with metric  $M_2(v_3, v_6) = 3$  and the path  $L_6(v_3, v_8) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8)$  with metric  $M_6(v_3, v_8) = 3$ . Distance vector from  $v_3$  to  $v_6$  equals  $R_2(v_3, v_6, v_2)$ . Distance vector from  $v_3$  to  $v_8$  equals  $R_6(v_3, v_8, v_2)$ .

From the table  $E = \|e_{i,j}\|$  let's define vertices  $v_9$  and  $v_{12}$  which are adjacent to the end vertex  $v_{10}$  of the path  $L_5(v_3, v_{10}) = (v_3 \rightarrow v_7 \rightarrow v_{10})$ . The vertex  $v_9$  is included to the path  $L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$ . That is why the path from  $v_{10}$  to  $v_9$  does not extend.

The path is formed  $L_5(v_3, v_{12}) = (v_3 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12})$  with metric  $M_5(v_3, v_{12}) = 3$ . Distance vector from  $v_3$  to  $v_{12}$  equals  $R_5(v_3, v_{12}, v_7)$ .

Thus, after the third iteration, these paths are formed:

$$L_2(v_3, v_6) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_6), M_2(v_3, v_6) = 3;$$

$$L_5(v_3, v_{12}) = (v_3 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12}), M_5(v_3, v_{12}) = 3;$$

$$L_6(v_3, v_8) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8), M_6(v_3, v_8) = 3.$$

Vectors' definitions  $R_2(v_3, v_6, v_2)$ ,  $R_5(v_3, v_{12}, v_7)$  and  $R_6(v_3, v_8, v_2)$  written in the table  $E = \|e_{i,j}\|$ .

Stage 4. From the table  $E = \|e_{i,j}\|$  let's define the vertex  $v_9$  which is adjacent to the end vertex  $v_6$  of the path  $L_2(v_3, v_6) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_6)$ . The vertex  $v_9$  is included in the path  $L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$ . That is why the path  $v_6$  to  $v_9$  does not extend.

From the table  $E = \|e_{i,j}\|$  let's define the vertex  $v_{13}$  which is adjacent to the end vertex  $v_{12}$  of the path  $L_5(v_3, v_{12}) = (v_3 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12})$ . The path is formed  $L_5(v_3, v_{13}) = (v_3 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12} \rightarrow v_{13})$  with metric  $M_5(v_3, v_{13}) = 4$ . Distance vector from  $v_3$  to  $v_{13}$  equals  $R_5(v_3, v_{13}, v_7)$ .

From the table  $E = \|e_{i,j}\|$  let's define vertices  $v_9$  and  $v_{11}$  which are adjacent to the end vertex  $v_8$  of the path  $L_6(v_3, v_8) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8)$ . The vertex  $v_9$  is included in the path  $L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$ . That is why the path from  $v_8$  to  $v_9$  does not extend.

The path is formed  $L_6(v_3, v_{11}) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8 \rightarrow v_{11})$  with metric  $M_6(v_3, v_{11}) = 4$ . Distance vector from  $v_3$  to  $v_{11}$  equals  $R_6(v_3, v_{11}, v_2)$ .

Thus, after the fourth iteration, these paths are formed:

$$L_5(v_3, v_{13}) = (v_3 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12} \rightarrow v_{13}), M_5(v_3, v_{13}) = 4;$$

$$L_6(v_3, v_{11}) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8 \rightarrow v_{11}), M_5(v_3, v_{11}) = 4.$$

Vectors' definitions  $R_5(v_3, v_{13}, v_7)$  and  $R_6(v_3, v_{11}, v_2)$  written in the table  $E = \|e_{i,j}\|$ .

Stage 5. From the table  $E = \|e_{i,j}\|$  let's define the vertex  $v_{13}$  which is adjacent to the end vertex  $v_{11}$  of the path  $L_6(v_3, v_{11})$ . The path is formed  $L_6(v_3, v_{13}) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8 \rightarrow v_{11} \rightarrow v_{13})$  with metric  $M_6(v_3, v_{13}) = 5$ . Distance vector from  $v_3$  to  $v_{13}$  equals  $R_6(v_3, v_{13}, v_2)$ .

Thus, after the fifth iteration, these paths are formed:

$$L_5(v_3, v_{13}) = (v_3 \rightarrow v_7 \rightarrow v_{10} \rightarrow v_{12} \rightarrow v_{13}), M_5(v_3, v_{13}) = 4;$$

$$L_6(v_3, v_{13}) = (v_3 \rightarrow v_2 \rightarrow v_5 \rightarrow v_8 \rightarrow v_{11} \rightarrow v_{13}), M_6(v_3, v_{13}) = 5.$$

Vectors' definitions  $R_5(v_3, v_{13})$ ,  $R_6(v_3, v_{13})$  written in the table  $E = \|e_{i,j}\|$ .

As a result, the table of vertices vectors is formed as in Table 18.

Table 18

Vertex  $v_4$  distance vectors overall

| $R_i(s,d)$  | $v_s$ | $v_d$    | $v_a$ | $M_i$ |
|-------------|-------|----------|-------|-------|
| $R_2(3,13)$ | $v_3$ | $v_{13}$ | $V_6$ | 3     |
| $R_3(3,13)$ | $v_3$ | $v_{13}$ | $V_2$ | 4     |
| $R_5(3,13)$ | $v_3$ | $v_{13}$ | $V_7$ | 4     |
| $R_6(3,13)$ | $v_3$ | $v_{13}$ | $V_2$ | 5     |

Values of the vectors of generated routes with a minimum metric are written in Table 19. This allows to determine the optimal paths from the beginning and all intermediate vertices to the final vertex without generating routes, which implies the time of creating traffic.

Table 19

Matrix of vectors of optimal paths (after the stages)

| $i \setminus j$ | $v_1$    | $v_2$    | $v_3$    | $v_4$    | $v_5$    | $v_6$    | $v_7$    | $v_8$    | $v_9$    | $v_{10}$ | $v_{11}$ | $v_{12}$ | $v_{13}$ |
|-----------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| $v_1$           | -        | $v_2$    | $\times$ | $\times$ | $\times$ | $v_2$    | $\times$ | $\times$ | $v_2$    | $\times$ | $\times$ | $\times$ | $v_2$    |
| $v_2$           | $\times$ | -        | $\times$ | $\times$ | $\times$ | $v_6$    | $\times$ | $\times$ | $v_6$    | $\times$ | $\times$ | $\times$ | $v_6$    |
| $v_3$           | $\times$ | $v_2$    | -        | $\times$ | $\times$ | $v_6$    | $\times$ | $\times$ | $v_6$    | $\times$ | $\times$ | $\times$ | $v_6$    |
| $v_4$           | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_5$           | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_6$           | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_7$           | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $v_9$    | $\times$ | $\times$ | $\times$ | $\times$ | $v_9$    |
| $v_8$           | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ |
| $v_9$           | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ | $\times$ | $v_{13}$ |
| $v_{10}$        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ | $\times$ |
| $v_{11}$        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ | $\times$ |
| $v_{12}$        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        | $\times$ |
| $v_{13}$        | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | $\times$ | -        |

In case of network reconfiguration or optimal path channel overload SDN controller makes changes to the optimal path vector table. Path reconfiguration is performed. For example, in case of overload on the path  $L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$   $a_{3,6} = v_3$  is removed from optimal path vector table (Table 19). New path is chosen  $L_3(v_3, v_{13}) = (v_3 \rightarrow v_2 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$  with path vector  $R_3(3,13) = (v_3, v_{13}, v_2, M_3)$ . Thus, value  $a_{3,2} = v_2$  is added to the vector table.

The existence of multiple paths permits dynamic path reconfiguration. For example, during the process of data transfer through path  $L_2(v_3, v_{13}) = (v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$  part of the path  $v_3 \rightarrow v_6$  turns out to be overloaded. SDN controller removes  $a_{3,6}$  from optimal path vector table

and adds values  $a_{3,7}=v_7$  and  $a_{7,9}=v_9$ . These values are formed using path vector  $R_2(3,13)=(v_3, v_{13}, v_6, M_2=3)$  and  $R_5(6,13)=(v_6, v_{13}, v_9, M_3=2)$ . As a result path  $L_2(v_3, v_{13})=(v_3 \rightarrow v_6 \rightarrow v_9 \rightarrow v_{13})$  is dynamically reconfigured to  $L_2(v_3, v_{13})=(v_3 \rightarrow v_7 \rightarrow v_9 \rightarrow v_{13})$ .

The main strength of this research is the new modified method that we propose. We were able to achieve greater network parameters in our solution such as traffic transferring and speed. Practical tests confirmed that this algorithm can be used on Edge architecture in various tasks benefitting from a drop in power consumption and aforementioned fault-tolerance.

Weaknesses of this method are that it only provides the way to transfer traffic but we do not take into account different types of data and potential nodes. These things are for our future research. Also, we tried our method only for a model, not for some real topology, and we also plan to do this in the future.

Additional opportunities of the solution arise from those of SDN – better speed, easier management, bigger scalability. Also, SDN is becoming more ubiquitous due to its high performance per watt ratio for Edge architecture and its high fault-tolerance in upscaled production environments.

The options proposed in this work are fully theoretical. A practical study and justification needed before a decision for possible implementation can be made. Therefore, the risks are obvious and related to the process of the practical use and implementation of the method.

#### 4. Conclusions

In this article we did a study of already known routing solutions for SDN networks and the results of their applied use, a method of calculating path metrics on the topology by the number of «hops» (transitions between network nodes), optimization of the route search procedure using SDN technological capabilities. Based on that, our own modified method of traffic construction is presented that allows usage of known paths to lower the time complexity of the routing procedure. Formation of routing information is performed centrally in the SDN controller.

Using the modified method of distance vector formation using a multipath wave algorithm allows for a prompt rerouting procedure to be performed, depending on changes in the network status.

The main advantage of this method is that it enables sophisticated networking tasks on edge architecture, where the number of connected clients is changing. Also, this SDN is less demanding than using specialized hardware, therefore improving both speed and cost for the edge network. Energy consumption for centralized management is also up to 41 % lower than decentralized routing methods, with lower (up to 47 % decrease) power consumption numbers observed during method testing.

Additionally, to balance the network load, it is necessary to perform the dynamic rerouting of paths based on the analysis of load of individual channels. For this task, channel utilization needs to be used as a metric.

#### Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial,

personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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