Fast ReRoute Model with Realization of Path and Bandwidth Protection Scheme in SDN

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Abstract. *The paper proposes a Fast ReRoute model with the realization of path and bandwidth protection scheme, which can be used in MPLS for SDN. The task of calculating the set of disjoint primary and backup paths during fast rerouting was reduced to solving the optimization problem of Integer Linear Programming. The advantage of the proposed solution is the possibility of implementing 1:1, 1:2, ..., 1:n path protection schemes without the introduction of an additional set of control (routing) variables, which contributes to reducing the dimension of the optimization problem being solved and the computational complexity of its practical implementation. The criterion of optimality of routing solutions contributes to the formation of the primary and backup disjoint paths with the highest possible bandwidth. In this case, the path with the maximum bandwidth will correspond to the primary path, while the remaining paths will be used as backup ones in decreasing order of their bandwidth. The total number of calculated disjoint paths depends on the selected redundancy scheme. The study conducted showed the efficiency and adequacy of the proposed Fast ReRoute model when using various redundancy schemes.*

Keywords

Bandwidth protection, disjoint paths, Fast ReRoute, integer linear programming, MPLS, optimization, path protection, SDN.

1. Introduction

As known, within the framework of Software-Defined Networks (SDN), the distribution of the data plane and control plane is performed. In this case, if a particular network element (link, node, segment or the entire path) fails, it must be detected, and the controller must take certain steps to quickly restore the transmission of the affected data flows [1], [2], [3] and [4]. The number and type of such failures, as well as the need for reconfiguration and rerouting calculations, increases the load on the network controllers. Existing Fast ReRoute (FRR) mechanisms for IP/Multi-Protocol Label Switching (IP/MPLS) networks can be migrated to SDN, but in this case, the OpenFlow switch limited routing tables and the complexity of FRR implementation should be taken into account [1] and [4].

During FRR, the implementation of the main schemes for protecting network elements from failures is a key technological challenge in deploying both enterprise and global SDNs of different types [5] and [6]. The multiservice of modern networks requires the implementation of not only schemes of protection of its topological elements–link, node, path, but also protection of the Quality of Service (QoS) level in the network as a whole [7] and [8]. As the first step in this direction, we can consider the protection of bandwidth [9], [10] and [11] with the future prospect of protecting other QoS indicators: the average end-to-end delay, the acceptable packet loss, etc. [7], [8] and [12].

In addition, it should be noted that FRR-related technological routing solutions may support the following redundancy schemes depending on resilience requirements [5] and [13]:

- 1+1 scheme, in which the data flow is transmitted both over the primary and over the backup route,
- 1:1 scheme, when for each primary route a backup one is created over which the data will be transmitted in case of failure of the primary path,

- n:1 scheme, in which one backup path is created for n primary paths (facility backup),
- 1:n scheme, in which n backup paths are created for one primary,
- n:m scheme, which is the most common case where m backup paths are supported for n primary (working) paths.

Quite often, the technical task of FRR is formulated as a task for calculating a set of disjoint paths [5], [14], [15] and [16]. This formulation of the task meets the requirements for increasing the fault-tolerance of routing solutions, especially in need of protection of paths and their bandwidth. Consequently, the actual scientific and practical task of developing and researching the Fast ReRoute model with a realization of the path and bandwidth protection scheme, which can be used in MPLS for SDN, seems to be relevant. In this case, the model should provide scalability of the resulting solutions and low computational complexity of their subsequent protocol implementation.

2. Related Work

An analysis of existing solutions has shown the relevance of developing approaches to fast rerouting in the direction of implementing MPLS in the SDN (Tab. 1). In general, modern approaches to the use of mechanisms for fast rerouting in the SDN when implementing various protection schemes of network elements, such as classical (link, node, etc.), and specific schemes for this type of networks, can be divided into heuristic, graph and flow-based [4], [17], [18], [19], [20], [21], [22], [23], [24] and [25]. A more detailed description of the solutions analyzed is presented in Tab. 1.

From Tab. 1, it is possible to conclude that the most common methods for solving FRR problems are heuristic approaches, and among the schemes for increasing resilience, the local protection (link, node or controller protection) is still prevalent. However, it is known that the flow-based approaches, usually based on the optimization of the rerouting tasks, which primarily aim at optimizing the use of available network resources, are the most promising [23], [24] and [25].

Among the disadvantages of existing solutions when implementing MPLS SDN FRR it should be noted that the implementation of the protection scheme of the path with a 1:n redundancy scheme, as a rule, leads to an increase in n times the size of the optimization problem in calculating the routes [9], [10], [11], [12] and [15]. If a solution is proposed for a multipath FRR, the need to formulate and solve a nonlinear optimization problem occurs [9]. These factors have a very critical impact on the computational complexity and scalability of protocol routing solutions that must be centrally obtained by an SDN controller.

Thus, the developed FRR model with a realization of the path and bandwidth protection scheme, which can be the basis for promising protocols for implementation of resilient SDN and Hybrid SDN, has formulated the following requirements:

- consideration of the flow-based nature of traffic,
- implementation of both classical protection schemes for network elements (link, node, path), and implementation of network bandwidth protection,
- linearity and scalable increase in the size of the optimization task.

3. Fast ReRoute Model with Realization of Path and Bandwidth Protection Scheme

The model presented in [26] is proposed for further modification, which will be used for the computation method of the set of disjoint primary and backup paths in fast rerouting oriented to the maximum path bandwidth.

In the framework of the modified model, the network structure is described by the graph $G = (R, E)$ in which $R = \left\{R_i;\ i = \overline{1,m}\right\}$ is a set of vertices that simulate routers, and $E = \left\{E_{i,j};\ i,j = \overline{1,m};\ i \neq j\right\}$ is a set of arcs representing links. Let each k th flow for transmitting in the network be associated with a number of functional parameters: s_k is the source node; d_k is the destination node; K is the set of flows for transmitting in the network ($k \in K$). In addition, the value $\varphi_{i,j}^k$ corresponds to the bandwidth of the link $E_{i,j} \in E$ available for the k th flow. Let us denote Bw^k as the demand to bandwidth of the k th flow.

As a result of solving the problem of calculating the set of disjoint primary and backup paths, it is necessary to calculate the set of variables $a_{i,j}^k$, each of which determines whether the link $E_{i,j} \in E$ belongs to the set of calculated disjoint paths for transmission of the k th flow. The number of control variables $a_{i,j}^k$ corresponds to the product $|K| \cdot |E|$.

The routing variables $a_{i,j}^k$ have the constraints of type:

$$a_{i,j}^k \in \{0; 1\}. \tag{1}$$

Tab. 1: MPLS SDN FRR related researches.

Ref.	Description of Contribution	Protection Scheme	Key Technologies Used
[17]	The mechanism of recovery for rerouting of flows in the case of link failures for multi-radio multi-channel Software-Defined Wireless Mesh Networks (SD-WMN) is proposed, where the recovery time and bandwidth of the communication links as key indicators for assessing the performance of recovery scenarios after failures are selected. Type of solution: heuristic. Advantages: reducing the recovery time compared to conventional routing protocols at the best achievable bandwidth.	Link protection	SD-WMN
[4]	The solution for local fast recovery in SDN without controller intervention in the case of a single node or link failure if it is topologically possible is proposed. The possibility of using (remote) loop-free alternates ((r) LFAs) in fast rerouting in SDN is shown. Type of solution: heuristic. Advantages: maximizing coverage, minimizing computational complexity, detecting and avoiding looping.	Link protection node protection	SDN, LFA
[18]	The mechanism of destination-specific Maximally Redundant Trees (dMRTs) with the aim of the use the fast rerouting (FRR) in SDN and Hybrid SDN is presented. Type of solution: heuristic. Advantages: less overhead in SDN, shorter backup path, high scalability.	Link protection, node protection	MPLS FRR, SDN, Hybrid SDN MRT
[19]	A fast failure recovery scheme in SDN under multi-controller concept is proposed, where the main controller is responsible for controlling the network in the normal state, while the other controllers are standby controllers for the network control in a failure state. For calculating the control paths and disjoint path planning, the use of the K-best path algorithm is proposed. Type of solution: heuristic. Advantages: recovery time is less than 50 ms, the mechanisms can be used for recovery after failures of both control and data paths.	Controller protection, link protection, node protection	SDN, Multi-controller, In-band controlled OpenFlow Networks
[20]	Proactive recovery schemes in SDN are proposed for local failures based on the aggregation of traffic flows, with a decrease in the involvement of controllers in this process, in order to reduce the requirements for the controller‘s computing power and the amount of control traffic generated during the recovery process. Type of solution: heuristic. Advantages: reduced recovery time and recovery specific control traffic, low memory requirement in switching components.	Link protection, node protection	SDN, Fast-Failover (FF)
[21]	The algorithm of Local Fast ReRoute (LFR) in SDN is proposed, where according to the flow aggregation strategy, LFR provides fast recovery by reducing the number of flow operations between the SDN controller and the switches. Type of solution: heuristic. Advantages: reduced the failure recovery time, minimized the total number of flow entries in the network.	Link protection	SDN, Local Fast ReRoute
[22]	The mechanism for updating routing and rerouting tables in case of the communication links failures in SDN with the support of acceptable QoS is proposed. Type of solution: graph model. Advantages: improving QoS by reducing packet routing delays and the data loss rate in case of a persistent link failure.	Link protection	SDN, IPFRR, QoS
[23]	The paper proposes a Hybrid-Hie solution for fast rerouting, which allows determining the ratio of the distribution of transmitted flows in the backup paths in accordance with their predicted utilization. Type of solution: flow-based model, optimization problem statement. Advantages: effective recovery in case of failure of interdomain communication links, load balancing, and recovery path stretch.	Link protection, multi-link protection	Hybrid SDN, SD-WAN, Traffic Engineering, Inter-domain routing, Intra-domain routing
[24]	The effective solution of optimizing restoration with segment routing in SDN is developed. Type of solution: flow-based model, optimization problem statement. Advantages: significant capacity benefits achievable from this optimized restoration with segment routing.	Link protection, node protection, Shared Local Restoration	SDN, Segment Routing
[25]	The bicriteria multiobjective algorithm with a maximum flow under minimum cost model to provide a balanced and resilient approach in an MPLS/SDN topology is proposed. Type of solution: optimization problem statement. Advantages: reduced routing complexity and path computation time, balanced network utilization, decreasing recovery time.	Link protection, node protection	MPLS/SDN, Traffic Engineering, QoS

In addition, the following conditions for a pair of source and destination nodes must be fulfilled [26]:

$$\sum_{j:E_{i,j}\in E} a_{i,j}^k = M^k;\ k \in K,\ R_i = s_k, \tag{2}$$

$$\sum_{j:E_{j,i}\in E} a_{i,j}^k = M^k;\ k \in K,\ R_i = d_k, \tag{3}$$

where M^k is an integer characterizing the number of disjoint primary and backup paths ($M^k > 1$) and used in the course of fast rerouting implementation in dependence with the type of redundancy scheme. Wherein M_k is defined as follows:

$$M^k = n + 1, \tag{4}$$

where n is the number of backup paths corresponding to the primary one in accordance with the redundancy scheme (1:1, 1:2, . . . , 1:n) which is necessary to realize.

At the same time, for the transit nodes in the network ($R_i \neq s_k, d_k$), there are restrictions imposed [26]:

$$\begin{cases} \sum\limits_{j:E_{j,i}\in E} a_{i,j}^k \le 1, & k \in K, \\ \sum\limits_{j:E_{j,i}\in E} a_{j,i}^k \le 1, & k \in K, \\ \sum\limits_{j:E_{i,j}\in E} a_{i,j}^k - \sum\limits_{j:E_{j,i}\in E} a_{j,i}^k = 0, & k \in K. \end{cases} \tag{5}$$

Let the value β be the lower bound of the bandwidth of links comprising the resulting routing solution and determining the performance of the worst bandwidth route. Then the following condition should be met (in analogy to [15]):

$$a_{i,j}^k \varphi_{i,j} + W(1 - a_{i,j}^k) \ge \beta, \tag{6}$$

where the weighting coefficient W takes the value, which is higher than the maximum bandwidth of links $E_{i,j} \in E$ belonging to the set of calculated disjoint paths available for the k th flow. The bandwidth protection condition can be formulated as follows:

$$\beta \ge Bw^k. \tag{7}$$

The function, which should be maximized, has been chosen as the optimality criterion of the solutions to the problem of calculating the set of disjoint primary and backup paths oriented to the maximization of path bandwidth:

$$J = \max_{a,\beta} \beta. \tag{8}$$

Thus, the task of calculating the set of disjoint primary and backup paths during fast rerouting was reduced to solving the optimization problem of Integer Linear Programming (ILP) with criterion Eq. (8) in the presence of linear constraints Eq. (1), Eq. (2), Eq. (3), Eq. (4) and Eq. (5), since the routing variables are Boolean. In addition, the model introduced protection conditions of the path Eq. (1), Eq. (2), Eq. (3), Eq. (4) and Eq. (5) and bandwidth Eq. (6) and Eq. (7). To implement the proposed real-time calculation model, the formulated ILP problem should be solved by heuristic methods, for example, ant colony optimization, simulated annealing, Hopfield networks, etc. [27] and [28].

In the course of solving the formulated optimization problem, we obtain a set of disjoint paths. Of this set, the path with the maximum bandwidth will correspond to the primary path, while the remaining paths will be used as a backup in decreasing order of their bandwidth. In this case, the total number of calculated paths depends on the selected redundancy scheme (1:1, 1:2, . . . , 1:n).

4. Numerical Research

The features of the proposed FRR model with realization of path and bandwidth protection scheme oriented to the maximization of path bandwidth will be demonstrated in the following example. The structure of the analyzed network, which is shown in Fig. 1, consists of seven routers and eleven communication links. Let the first router be the source node, and the seventh router the destination node.

As an example of the network structure under consideration (Fig. 1), we have the following set of possible paths between the first and seventh routers:

- $L_1 = \{E_{1,2}, E_{2,5}, E_{5,7}\}$,
- $L_2 = \{E_{1,3}, E_{3,6}, E_{6,7}\}$,
- $L_3 = \{E_{1,4}, E_{4,7}\}$,
- $L_4 = \{E_{1,4}, E_{4,6}, E_{6,7}\}$,
- $L_5 = \{E_{1,3}, E_{3,5}, E_{5,7}\}$,
- $L_6 = \{E_{1,2}, E_{2,7}\}$.

In Fig. 1, in the gaps of the communication links, their capacities are shown, the bold lines show the calculated set of disjoint routes, and the dotted lines show the unused routes in the routing solution. Consider, for example, a case of the routing order when it is necessary to realize the redundancy scheme 1:2 with calculating one primary and two backup paths. Then, in the computation, out of the set of disjoint primary and backup routes where $M^k = 3$ for transmitting the k th flow, four variants of the set of disjoint paths can be obtained (Tab. 2). The results of the simulation have been obtained within the MATLAB environment, which uses the modified branch-and-bound procedure to find feasible points during solving the ILP optimization task. The exact solution of the ILP problem achieved in this way can act as a reference in the analysis of the effectiveness of approximate calculation methods.

Tab. 2: Sets of three paths between the first and seventh routers and their bandwidth.

Set of Disjoin Paths		Links of Path	Path Bandwidth (1/s)
1	L_1	$\{E_{1,2}, E_{2,5}, E_{5,7}\}$	190
	L_2	$\{E_{1,3}, E_{3,6}, E_{6,7}\}$	160
	L_3	$\{E_{1,4}, E_{4,7}\}$	185
2	L_4	$\{E_{1,4}, E_{4,6}, E_{6,7}\}$	160
	L_5	$\{E_{1,3}, E_{3,5}, E_{5,7}\}$	210
	L_6	$\{E_{1,2}, E_{2,7}\}$	180
3	L_3	$\{E_{1,4}, E_{4,7}\}$	185
	L_5	$\{E_{1,3}, E_{3,5}, E_{5,7}\}$	210
	L_6	$\{E_{1,2}, E_{2,7}\}$	180
4	L_2	$\{E_{1,3}, E_{3,6}, E_{6,7}\}$	160
	L_3	$\{E_{1,4}, E_{4,7}\}$	185
	L_6	$\{E_{1,2}, E_{2,7}\}$	180

Let the $Bw^1 = 180$ 1/s. The application of the proposed model Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5), Eq. (6), Eq. (7) and Eq. (8) made it possible to calculate the optimal set of disjoint paths for fast rerouting oriented to the maximum bandwidth of network links comprised of the paths. In the presented case, the optimal solution is provided by the set of disjoint paths L_3, L_5, and L_6 (Fig. 1) with the maximum values of paths bandwidth (Tab. 2). Here, the path L_5 is chosen as the primary one because of its path bandwidth value of 210 1/s, which is the maximum of the three paths comprising the set of routes. Accordingly, the paths L_3 and L_6 are selected as the backup routes.

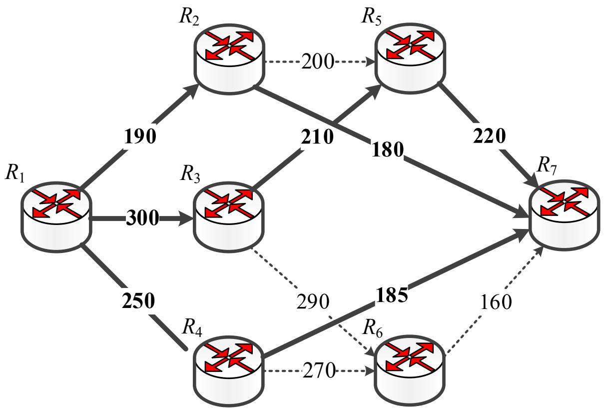

Fig. 1: Set of optimal primary and backup paths ($M^k = 3$).

Next, consider the case of a 1:1 redundancy scheme. Here it is necessary to calculate two disjoint paths (primary and backup) with the maximum bandwidth at $M^k = 2$ (Tab. 3). In Fig. 2, the previous designations are used. However, in the gaps of the network links, their changed capacities are shown and chosen as new input data.

Tab. 3: Sets of two paths between the first and seventh routers and their bandwidth.

Set of Disjoin Paths		Links of Path	Path Bandwidth (1/s)
1	L_1	$\{E_{1,2}, E_{2,5}, E_{5,7}\}$	180
	L_2	$\{E_{1,3}, E_{3,6}, E_{6,7}\}$	190
2	L_1	$\{E_{1,2}, E_{2,5}, E_{5,7}\}$	180
	L_3	$\{E_{1,4}, E_{4,7}\}$	210
3	L_1	$\{E_{1,2}, E_{2,5}, E_{5,7}\}$	180
	L_4	$\{E_{1,4}, E_{4,6}, E_{6,7}\}$	185
4	L_3	$\{E_{1,4}, E_{4,7}\}$	210
	L_5	$\{E_{1,3}, E_{3,5}, E_{5,7}\}$	180
5	L_4	$\{E_{1,4}, E_{4,6}, E_{6,7}\}$	185
	L_5	$\{E_{1,3}, E_{3,5}, E_{5,7}\}$	180
6	L_3	$\{E_{1,4}, E_{4,7}\}$	210
	L_6	$\{E_{1,2}, E_{2,7}\}$	200
7	L_2	$\{E_{1,3}, E_{3,6}, E_{6,7}\}$	190
	L_6	$\{E_{1,2}, E_{2,7}\}$	200

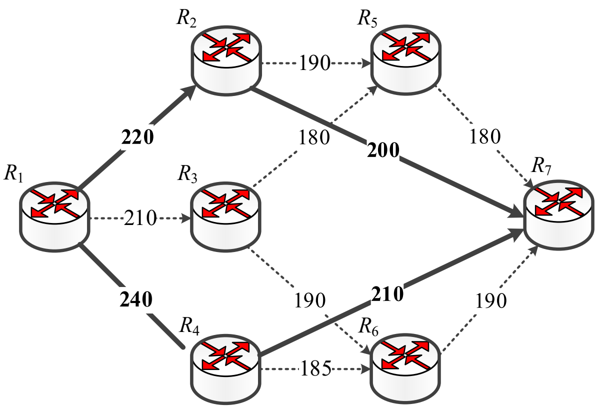

Fig. 2: Set of optimal primary and backup paths ($M^k = 2$).

In this case, accept $Bw^1 = 190$ 1/s. Possible variants of sets of disjoint paths consisting of two routes are shown in Tab. 3. Here, the paths L_3 and L_6 are chosen as the optimal solution (Fig. 2). In this case, the path L_3 is chosen as the primary one, since it has a greater bandwidth (210 1/s) than the path (200 1/s), which in turn will be used as a backup. This set of paths has the maximum bandwidth and satisfies the condition of its protection Eq. (7) in accordance with the requirements of the transmitted flow in the process of fast rerouting.

Thus, the conducted research has shown the efficiency and adequacy of the proposed FRR model and the 1:n redundancy scheme. Here we should note the important advantage of the model from the computational point of view, due to the absence of the need to introduce additional types of variables, as was done in [9], [10],[11] and [15], i.e. the dimension of the optimization problem does not increase.

5. Conclusion

The paper proposes a solution to an actual scientific and practical problem associated with the development and research of the FRR model with the realization of the path and bandwidth protection scheme and the $1{:}n$ redundancy scheme. Therefore, the task of calculating the set of disjoint primary and backup paths during fast rerouting was reduced to solving the optimization problem of ILP with criterion Eq. (8) in the presence of linear constraints Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5), Eq. (6) and Eq. (7), since the routing variables are Boolean. Further, from the calculated set, the path with the maximum bandwidth will correspond to the primary path, while the remaining paths will be used as backup ones. In this case, the total number of calculated paths depends on the selected redundancy scheme ($1{:}1$, $1{:}2$, $\ldots$, $1{:}n$).

The main technological advantages of the proposed model include the following:

- the FRR provides the implementation of a path protection scheme when conditions Eq. (1), Eq. (2), Eq. (3), Eq. (4) and Eq. (5) are met,
- the bandwidth protection is ensured by fulfilling conditions Eq. (6) and Eq. (7),
- the proposed solution is aimed at maximizing the bandwidth of the paths used and of the communication links that compose them, for which the corresponding conditions Eq. (6) and Eq. (8) are met,
- the possibility of implementing various redundancy schemes ($1{:}1$, $1{:}2$, $\ldots$, $1{:}n$) is introduced when conditions Eq. (1), Eq. (2), Eq. (3) and Eq. (4) are met.

It is important to note that the advantages from the computational point of view include the linearity of the proposed model of fast rerouting, as well as the fact that the implementation of the $1{:}n$ scheme does not increase the dimension of the optimization problem. The development of the model is seen in the selection of a set of paths under other indicators of QoS and Quality of Experience (QoE), as well as security indicators.

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References

[1] MONGE, A. S. and K. G. SZARKOWICZ. *MPLS in the SDN Era: Interoperable Scenarios to Make Networks Scale to New Services*. 1st ed. Boca Raton: O'Reilly Media, 2016. ISBN 978-1-4919-0545-6.

[2] PEREPELKIN, D., M. IVANCHIKOVA and A. IVUTIN. Fast rerouting algorithm in distributed computer networks based on subnet routing method. In: *2017 27th International Conference Radioelektronika (RADIOELEKTRONIKA)*. Brno: IEEE, 2017, pp. 1–4. ISBN 978-1-5090-4591-4. DOI: 10.1109/RADIOELEK.2017.7936648.

[3] RAK, J., D. PAPADIMITRIOU, H. NIEDERMAYER and P. ROMERO. Information-driven network resilience: Research challenges and perspectives. *Optical Switching and Networking*. 2017, vol. 23, iss. 2, pp. 156–178. ISSN 1573-4277. DOI: 10.1016/j.osn.2016.06.002.

[4] MERLING, D., W. BRAUN and M. MENTH. Efficient Data Plane Protection for SDN. In: *2018 4th IEEE Conference on Network Softwarization and Workshops (NetSoft)*. Montreal: IEEE, 2018, pp. 10–18. ISBN 978-1-5386-4633-5. DOI: 10.1109/NETSOFT.2018.8459923.

[5] RAK, J. *Resilient Routing in Communication Networks*. 1st ed. Cham: Springer, 2015. ISBN 978-3-319-22332-2.

[6] MAUTHE, A., D. HUTCHISON, E. K. CETINKAYA, I. GANCHEV, J. RAK, J. P. G. STERBENZ, M. GUNKELK, P. SMITH and T. GOMES. Disaster-resilient communication networks: Principles and best practices. In: *2016 8th International Workshop on Resilient Networks Design and Modeling (RNDM)*. Halmstad: IEEE, 2016, pp. 1–10. ISBN 978-1-4673-9023-1. DOI: 10.1109/RNDM.2016.7608262.

[7] LEMESHKO, A. V., O. Y. EVSEEVA and S. V. GARKUSHA. Research on Tensor Model of Multipath Routing in Telecommunication Network with Support of Service Quality by Greate Number of Indices. *Telecommunications and Radio Engineering*. 2014, vol. 73, iss. 15, pp. 1339–1360. ISSN 1943-6009. DOI: 10.1615/TelecomRadEng.v73.i15.30.

[8] LEMESHKO, O. V. and O. S. YEREMENKO. Dynamics analysis of multipath QoS-routing tensor model with support of different flows classes. In: *2016 International Conference on Smart Systems and Technologies (SST)*. Osijek:

IEEE, 2016, pp. 225–230. ISBN 978-1-5090-3720-9. DOI: 10.1109/SST.2016.7765664.

[9] LEMESHKO, O., K. AROUS and N. TARIKI. Effective solution for scalability and productivity improvement in fault-tolerant routing. In: *2015 Second International Scientific-Practical Conference Problems of Infocommunications Science and Technology (PIC S&T)*. Kharkiv: IEEE, 2015, pp. 76–78. ISBN 978-9-6697-5192-8. DOI: 10.1109/INFOCOMMST.2015.7357274.

[10] LEMESHKO, O. and O. YEREMENKO. Enhanced method of fast re-routing with load balancing in software-defined networks. *Journal of Electrical Engineering*. 2017, vol. 68, iss. 6, pp. 444–454. ISSN 1339-309X. DOI: 10.1515/jee-2017-0079.

[11] LEMESHKO, O. and O. YEREMENKO. Linear optimization model of MPLS Traffic Engineering Fast ReRoute for link, node, and bandwidth protection. In: *2018 14th International Conference on Advanced Trends in Radioelecrtronics, Telecommunications and Computer Engineering (TCSET)*. Slavske: IEEE, 2018, pp. 1009–1013. ISBN 978-1-5386-2556-9. DOI: 10.1109/TCSET.2018.8336365.

[12] LEMESHKO, O. V., S. V. GARKUSHA, O. S. YEREMENKO and A. M. HAILAN. Policy-based QoS management model for multiservice networks. In: *2015 International Siberian Conference on Control and Communications (SIBCON)*. Omsk: IEEE, 2015, pp. 1–4. ISBN 978-1-4799-7103-9. DOI: 10.1109/SIBCON.2015.7147124.

[13] HAIDER, A. and R. HARRIS. Recovery techniques in next generation networks. *IEEE Communications Surveys & Tutorials*. 2007, vol. 9, iss. 3, pp. 2–17. ISSN 1553-877X. DOI: 10.1109/COMST.2007.4317617.

[14] ALOUNEH, S., A. AGARWAL and A. EN-NOUAARY. A novel path protection scheme for MPLS networks using multi-path routing. *Computer Networks: The International Journal of Computer and Telecommunications Networking*. 2009, vol. 53, iss. 9, pp. 1530–1545. ISSN 1389-1286. DOI: 10.1016/j.comnet.2009.02.001.

[15] CRUZ, P., T. GOMES and D. MEDHI. A Heuristic for Widest Edge-disjoint Path Pair Lexicographic Optimization. In: *2014 6th International Workshop on Reliable Networks Design and Modeling (RNDM)*. Barcelona: IEEE, 2014, pp. 9–15. ISBN 978-1-4799-7040-7. DOI: 10.1109/RNDM.2014.7014925.

[16] YEREMENKO, O. Enhanced flow-based model of multipath routing with overlapping by nodes paths. In: *2015 Second International Scientific-Practical Conference Problems of Infocommunications Science and Technology (PIC S&T)*. Kharkiv: IEEE, 2015, pp. 42–45. ISBN 978-9-6697-5192-8. DOI: 10.1109/INFOCOMMST.2015.7357264.

[17] TANHA, M., D. SAJJADI and J. PAN. Demystifying Failure Recovery for Software-Defined Wireless Mesh Networks. In: *2018 4th IEEE Conference on Network Softwarization and Workshops (NetSoft)*. Montreal: IEEE, 2018, pp. 488–493. ISBN 978-1-5386-4633-5. DOI: 10.1109/NETSOFT.2018.8460087.

[18] BRAUN, W., D. MERLING and M. MENTH. Destination-specific maximally redundant trees: Design, performance comparison, and applications. In: *2018 21st Conference on Innovation in Clouds, Internet and Networks and Workshops (ICIN)*. Paris: IEEE, 2018, pp. 1–8. ISBN 978-1-5386-3458-5. DOI: 10.1109/ICIN.2018.8401580.

[19] CHAN, K.-Y., C.-H. CHEN, Y.-H. CHEN, Y.-J. TSAI, S. S. W. LEE and C.-S. WU. Fast Failure Recovery for In-Band Controlled Multi-Controller OpenFlow Networks. In: *2018 International Conference on Information and Communication Technology Convergence (ICTC)*. Jeju: IEEE, 2018, pp. 396–401. ISBN 978-1-5386-5041-7. DOI: 10.1109/ICTC.2018.8539715.

[20] THORAT, P., S. JEON and H. CHOO. Enhanced local detouring mechanisms for rapid and lightweight failure recovery in OpenFlow networks. *Computer Communications*. 2017, vol. 108, iss. 1, pp. 78–93. ISSN 0140-3664. DOI: 10.1016/j.comcom.2017.04.005.

[21] ZHANG, X., Z. CHENG, R.P. LIN, L. HE, S. YU and H. LUO. Local Fast Reroute With Flow Aggregation in Software Defined Networks. *IEEE Communications Letters*. 2017, vol. 21, iss. 4, pp. 785–788. ISSN 1558-2558. DOI: 10.1109/LCOMM.2016.2638430.

[22] MYOUPO, J. F., Y. F. YANKAM and V. K. TCHENDJI. A Centralized and Conflict-Free Routing Table Update Method through Triplets' Lists Vector in SDN Architectures. In: *2018 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI)*. Guangzhou: IEEE, 2018, pp. 1509–1515.

ISBN 978-1-5386-9381-0. DOI: 10.1109/SmartWorld.2018.00261.

[23] JIA, X., Y. JIANG and J. ZHU. Link fault protection and traffic engineering in hybrid SDN networks. In: *IEEE Conference on Computer Communications Workshops (INFOCOM Wksps)*. Honolulu: IEEE, 2018, pp. 853–858. ISBN 978-1-5386-5979-3. DOI: 10.1109/INFCOMW.2018.8406823.

[24] HAO, F., M. KODIALAM and T. V. LAKSHMAN. Optimizing restoration with segment routing. In: *The 35th Annual IEEE International Conference on Computer Communications (INFOCOM)*. San Francisco: IEEE, 2016, pp. 1–9. ISBN 978-1-4673-9953-1. DOI: 10.1109/INFOCOM.2016.7524551.

[25] ALHAQBANI M. and H. LIU. Conceptual Mechanism Software Defined Network Topology in Multiprotocol Label Switching Network Domain. In: *International Conference on Computational Science and Computational Intelligence (CSCI)*. Las Vegas: IEEE, 2017, pp. 680–684. ISBN 978-1-5386-2652-8. DOI: 10.1109/CSCI.2017.117.

[26] LEMESHKO, O., O. YEREMENKO, M. YEVDOKYMENKO, B. SLEIMAN, A.M. HAILAN and A. MERSNI. Computation Method of Disjoint Paths under Maximum Bandwidth Criterion. In: *2019 3rd International Conference on Advanced Information and Communications Technologies (AICT)*. Lviv: IEEE, 2019, pp. 161–164. ISBN 978-1-7281-2399-8. DOI: 10.1109/AIACT.2019.8847756.

[27] SIERKSMA, G. and Y. ZWOLS. *Linear and Integer Optimization: Theory and Practice, Third Edition (Advances in Applied Mathematics)*. 3rd ed. CRC Pres, 2015. ISBN 978-1-4987-1016-9.

[28] WANG, Y. and J. DOUCETTE. ILP-based heuristic method for the multi-period survivable network augmentation problem. In: *2016 8th International Workshop on Resilient Networks Design and Modeling (RNDM)*. Halmstad: IEEE, 2016, pp. 58–65. ISBN 978-1-4673-9023-1. DOI: 10.1109/RNDM.2016.7608268.

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