Enhanced Flow-based Model of Multipath Routing with Overlapping by Nodes Paths

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***Abstract*—Enhanced solution of topical scientific and practical problem associated with the development of flow-based model of multipath routing with paths overlapping by nodes in Telecommunication Network (TCN) was presented. This model is further extension of the well known multipath routing model based on the introduction to the structure of non-linear constraints responsible for the calculation of routes that intersect just at nodes. It is possible to obtain the order of multipath routing by overlapping by nodes paths in the solution of nonlinear programming problem with given objective function, linear constraints and nonlinear terms. Search for a compromise on the providing fault-tolerance and network security, on the one hand, and quality of service, on the other, led to the fact that in some important cases the requirements for overlapping paths can be slightly reduced and it is allowable to use paths overlapping only by network nodes. Simulation results confirmed the efficiency of the proposed model. Among the advantages of the proposed model of multipath routing with overlapping by nodes paths, one can distinguish the fact that with the same parameters of security and fault-tolerance can be achieved higher performance and quality of service parameters in TCN in a whole.**

Keywords—multipath routing; flow-based model; multiflow; Quality of Service; Network Security; Fault-tolerance; non-overlapping paths; overlapping by nodes paths

I. Introduction

Adoption of infocommunication services and improvement of technologies for ensuring the Quality of Service (QoS) are mainly characterize the development of telecommunication networks (TCN) nowadays. An important place is taken by routing protocols within this process. In turn, the sufficient choice of paths for packets transmission between a pair of nodes sender and receiver determines the numerical values of end-to-end QoS parameters: average delay, jitter, packet loss probability and the performance of TCN in a whole [1, 2]. Almost all modern routing protocols have improved their functionality by support of multipath routing. Practical and scientific research findings showed [2-4] that multipath routing improves the QoS parameters by providing load balancing across multiple paths.

An important place in using of multipath routing takes also increasing of fault-tolerance and security in TCN with traditional use of routing over multiple disjoint paths [5-7], where are common components only the sender and receiver of packets. Using non-overlapping routes ensures that failure or compromise of a network element (node or link) will result in failure or compromise of only one rather than several routes [8-10], which takes place at the routing of overlapping paths. However, the implementation of multipath routing over non-overlapping paths as a result uses a network resource inefficiently that is common to multiple paths. This tends to have a negative impact on the TCN performance and quality of service in the network as a whole.

Search for a compromise on the providing fault-tolerance and security, on the one hand, and quality of service, on the other, led to the fact that in some important cases the requirements for overlapping paths can be slightly reduced and it is allowable to use paths overlapping, for example, only by TCN nodes. In these routes not only sender and receiver are common, but some transit nodes, anyway they do not contain the shared communication links. This is relevant in the case when, for example, the place of failures is radio channel. Moreover, the operational reliability of node, which operates on the basis of modern switching equipment, can meet the availability factor 0.99999 [3]. Another example is the fact that the wireless radio channel of TCN is also a major source of compromise of data transmitted on OSI physical layer [6, 7]. That is exactly in such cases where the failures and/or compromise are inclined links, but not nodes of TCN it is advisable to use overlapping by nodes paths, because it can lead to increased network performance with providing the same level of fault-tolerance or security as using the non-overlapping paths.

For paths calculation in multipath routing the graph theory models and algorithms are mainly used [3, 5], the advantages of which are usually related to low computational complexity and high scalability. An example of this is the modification of Dijkstra's algorithm [11], which form the basis of the multipath routing protocols SMR (Split Multipath Routing) and AODVM (AODV-Multipath), used in wireless TCN, as well as secure routing in MANET according to the protocol SPREAD (Secure Protocol for REliable dAta Delivery) [6, 7].

Despite these advantages, graph theory solutions have some important drawbacks. First of all, the lack of using the characteristics of transmitted packet flows makes it difficult to work with mechanisms of combating congestion in TCN communication links, and complexity of calculation and control the amount of used paths. In connection with this more attention is paid to use of the flow-based models [2, 4], in which characteristics of network traffic are taken into account more fully than with graph theory models.

Therefore, scientific and practical problems associated with the development of new mathematical models of multipath routing with paths overlapping by nodes are topical. In addition, these models can be the basis of relevant routing protocols to provide a required level of quality of service, improve the security of transmitted data, as well as fault-tolerance and efficient use of network resources.

II. Flow-based Model of Multipath Routing by Non-overlapping Paths

It is known that the paths used in the multipath routing are divided into following classes. The first class is the non-overlapping paths, which are defined as routes where only source and destination nodes are common. If paths contain at least one common node and (or) link they are called overlapping. If paths have common nodes they are called paths overlapping by nodes, and if they contain common links such routes belong to class of paths overlapping by links.

In [12] proposed a flow-based model of multipath routing by non-overlapping paths with the ability to control the number of routes used, as it is performed in [6, 8], for example. Development of a flow-based model of multipath routing by non-overlapping paths was based on the model proposed in [2]. In doing so, its advantages include taking into account features like network structure, parameters of communication links and traffic characteristics, support of multiflow transmission. In addition, it allows the control of possible network elements overload by fulfillment the conditions of the flow conservation in the network nodes and conditions to prevent overloading of communication links.

Within the basic model the network structure is described by weighted oriented graph $G=(V,E)$, where V is a set of vertices (routers), and E is a set of graph arcs (communication links). Every link $(i,j)\in E$ is weighted by the parameter $c_{i,j}$ characterizing the throughput of the modeling communication link. Let S_k and D_k be source and destination nodes of the k-th flow respectively, and r^k be the k-th flow rate from the set K. Quantity $x_{i,j}^k$ is a control variable, which characterizes the part of k-th flow of the link $(i,j)\in E$. In accordance with the physics of the multipath routing problem being solved the following restrictions for the variables are needed:

$$0\le x_{i,j}^k \le 1. \qquad (1)$$

For the purpose of prevention of network nodes overload it is necessary to meet the condition of flow conservation on the source, transit and destination nodes, respectively:

$$\begin{cases} \sum\limits_{j:(i,j)\in E} x_{i,j}^k - \sum\limits_{j:(j,i)\in E} x_{j,i}^k = 1,\ i=S_k; \\ \sum\limits_{j:(i,j)\in E} x_{i,j}^k - \sum\limits_{j:(j,i)\in E} x_{j,i}^k = 0,\ i\ne S_k, D_k; \\ \sum\limits_{j:(i,j)\in E} x_{i,j}^k - \sum\limits_{j:(j,i)\in E} x_{j,i}^k = -1,\ i=D_k. \end{cases} \qquad (2)$$

Also, to prevent the communication links overload the next conditions must be met:

$$\sum_{k\in K} r_k \cdot x_{i,j}^k \le c_{i,j}, \quad (i,j)\in E. \qquad (3)$$

In solving the routing problem it is reasonable to minimize the following objective function:

$$J=\sum_{k\in K}\sum_{(i,j)\in E} f_{i,j}\cdot x_{i,j}^k, \qquad (4)$$

where $f_{i,j}$ is the links metric between i-th and j-th nodes of TCN.

For multipath routing by non-overlapping paths it is necessary to satisfy the following assumption: at each transit node input flow should enter from not more than one communication link, and therefore, it does not departure for more than one outgoing link. Accordingly, in the notation of the basic model (1)-(4) for all input interfaces of i-th transit node must be met the following conditions:

$$\sum_{j:(j,i)\in E}\ \sum_{\substack{l:(l,i)\in E,\\ l\ne j}} x_{j,i}^k x_{l,i}^k = 0, \qquad (5)$$

but for all output interfaces of i-th transit node we have

$$\sum_{n:(i,n)\in E}\ \sum_{\substack{m:(i,m)\in E,\\ m\ne n}} x_{i,n}^k x_{i,m}^k = 0. \qquad (6)$$

Performing nonlinear constraints (5) and (6) ensures that the flow through i-th transit node received from not more than one adjacent node and transmitted to not more than one adjacent node. Thus it is formed a set of non-overlapping paths where only a pair of sender and receiver nodes are common. Because of the nonlinearity of the conditions (5) and (6) optimization problem associated with the minimization of expression (4) refers to a class of nonlinear programming problems.

In order to control the number of non-overlapping paths used in realization of multipath routing of k-th flow upper bound of number of disjoint paths is denoted by the M_{UB}^k, which is determined by the degree of the vertices modeling source and destination nodes, i.e., the number of arcs (links) incident to these vertices:

$$M_{UB}^k = \mathbf{min}\big(d(S_k), d(D_k)\big), \qquad (7)$$

where $d(S_k)$ and $d(D_k)$ are source and destination vertices (nodes) degrees of k-th flow, respectively.

In fact, the number of non-overlapping paths for k-th flow routing using model (1)-(4) and conditions (5), (6) in analogy to expression (7) can be calculated as follows:

$$M^k = \sum_{j:(j,i)\in E} \left\lceil x_{i,j}^k \right\rceil \text{ or } M^k = \sum_{n:(n,m)\in E} \left\lceil x_{n,m}^k \right\rceil$$
$$\text{for } i = S_k,\ m = D_k, \tag{8}$$

where $\lceil \cdot \rceil$ is ceiling operation which means rounding to the nearest higher whole number; $\sum_{j:(j,i)\in E} \left\lceil x_{i,j}^k \right\rceil$ is the number of output interfaces through which the k-th flow exits the source node; $\sum_{n:(n,m)\in E} \left\lceil x_{n,m}^k \right\rceil$ is the number of input interfaces through which the k-th flow enters the destination node.

The value M^k can be used as an evaluated parameter and as a regulated variable, i.e., it can help to define the minimum, maximum, or to determine a specified number of non-overlapping paths used in multipath routing. The limits of this parameter are determined by next inequality:

$$1 \le M^k \le M_{UB}^k. \tag{9}$$

III. Flow-Based Model of Multipath Routing with Paths Overlapping by Nodes

Consider the case when it is required to implement multipath routing with paths overlapping by nodes. In this model the following assumption (hypothesis) for all input and output interfaces used by i-th transit node is necessary. Every input flow of a given intensity also should correspond to the output flow of the same intensity:

$$\sum_{m=1}^{N_{in}} \prod_{n=1}^{N_{out}} x_{m,i}^k \left(x_{m,i}^k - x_{i,n}^k \right) = 0, \tag{10}$$

where N_{in} is the number of input interfaces of i-th transit node; N_{out} is the number of output interfaces of i-th transit node. Also should be performed the opposite condition: each output flow of a given intensity should correspond to the input flow of exactly the same intensity:

$$\sum_{n=1}^{N_{out}} \prod_{m=1}^{N_{in}} x_{i,n}^k \left(x_{i,n}^k - x_{m,i}^k \right) = 0. \tag{11}$$

Performing nonlinear constraints (10) and (11) ensures that the flows that pass through i-th transit node come from the same number of contiguous nodes as transmitted to other adjacent nodes with exactly the same intensity. Thus, there is forming a set of overlapping paths with not only common pair of source and destination nodes, as well as using common transit nodes. The ability to control the number of routes used with expressions (7)-(9), as is done in [12], can be applied in the case of paths overlapping by nodes in the same manner.

IV. Research of Represented Multipath Routing Flow-Based Models

Suppose it must be solved the problem of multipath routing with paths overlapping by nodes for multiflow traffic transmission. In solving the problem using the proposed flow-based model was investigated a network of seven nodes and twelve communication links shown on Fig. 1. At the same time as a pair of source-destination nodes were used the first and seventh nodes, respectively. On the network links was shown available throughput, which is measured in packets per second (1/s) (Fig. 1).

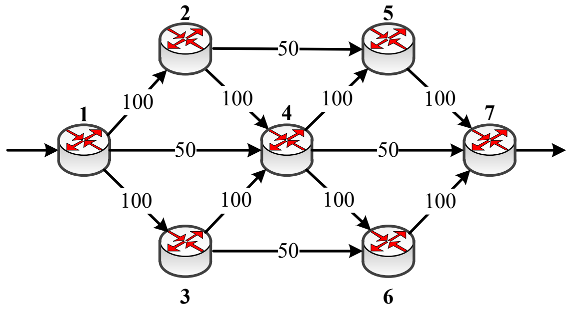

Fig. 1. Structure of investigated TCN.

For illustration consider an example where in the multipath routing it should be minimized the number of hops, when $f_{i,j} = 1$. Then the maximum performance towards the routes between first and seventh nodes of TCN in the implementation of multipath routing with paths overlapping by nodes will be 250 1/s (Fig. 2). On Fig. 2 on links it was shown the intensity of every flow over them. Not involved in the routing links depicted by the dashed lines.

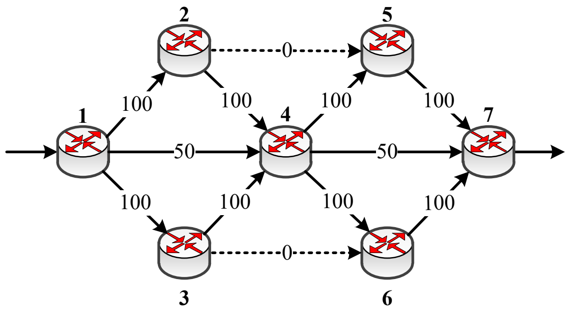

Fig. 2. The result of calculation the set of paths overlapping by nodes using conditions (10) and (11) with flow intensity 250 1/s.

As it can be seen, in transmission the flow with intensity 250 1/s obtained set of routes includes the next three ($M^k = 3$) paths: 1→4→7, 1→2→4→5→7 and 1→3→4→6→7 overlapping by nodes. In this case these paths have one common node, namely, transit node 4. By the path 1→4→7 transmitted flow of 50 1/s, and by the paths 1→2→4→5→7 and 1→3→4→6→7 transmitted flows of intensities 100 1/s.

Whereas, for example, using a set of non-overlapping paths (Fig. 3), the performance of communication direction between the first and seventh nodes with the throughput of communication links indicated on Fig. 1 is

150 1/s. Thus, using of paths overlapping by nodes, in this example, leads to an increase in performance of the selected communication direction about 1.7 times.

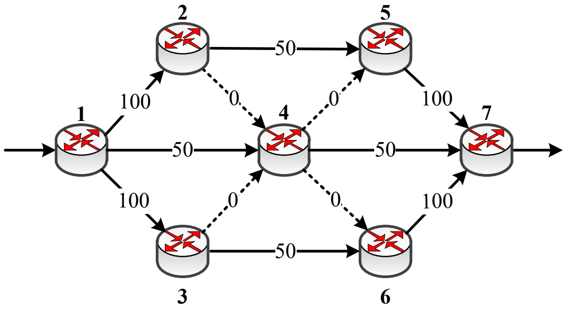

Fig. 3. The result of calculation the set of non-overlapping paths with flow intensity 150 1/s.

V. Conclusion

In presented research it was proposed a solution of actual scientific and practical problem associated with the development of the flow-based model of multipath routing with paths overlapping by nodes in telecommunication network. Proposed model is a further extension of the well-known model of multipath routing [2] due to the introduction in its structure of non-linear constraints (10) and (11). It is possible to obtain the order of multipath routing with paths overlapping by nodes in solving nonlinear programming problem with the objective function (4), linear constraints (1)-(3) and non-linear conditions (10) and (11). The use of conditions (10) and (11) allows the calculation of the set of routes that intersect just at nodes.

Among the advantages of using the proposed model of multipath routing with paths overlapping by nodes are the following. Search for a compromise in fault-tolerance and security on the one hand, and the quality of service, on the other, in some cases the requirements to intersecting of paths can be reduced, and it is allowable the use of paths that intersect at nodes. This is possible in cases when just communication links susceptible to failures and/or compromise instead of TCN nodes. In addition, the operational reliability of nodes of transport network based on modern switching equipment may correspond to availability factor of 0.99999. So, under the same parameters of security and fault-tolerance it is possible to increase the performance of TCN and Quality of Service in a whole.

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